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PHASE II FINAL REPORT

ADVANCED SUPERSONIC PROPULSION STUDY

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16. Abstract

A continuation of the NASA/P&WA study to evaluate various types of propulsion systems for advanced commercial supersonic transports has resulted in the identification of two very promising engine concepts. They are the Variable Stream Control Engine which provides independent temperature and velocity control for two coannular exhaust streams, and a derivative of this engine, a Variable Cycle Engine that employs a rear flow-inverter valve to vary the bypass ratio of the cycle. Both concepts are based on advanced engine technology and have the potential for significant improvements in jet noise, exhaust emissions and economic characteristics relative to current technology supersonic engines. Extensive research and technology programs are required in several critical areas that are unique to these supersonic Variable Cycle Engines to realize these potential improvements. In this report, parametric cycle and integration studies of conventional and Variable Cycle Engines are reviewed, features of the two most promising engine concepts are described, and critical technology requirements and required programs are summarized.

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FOREWORD

This report summarizes a contracted study of advanced supersonic propulsion systems conducted for NASA by Pratt & Whitney Aircraft and, in a subcontractor role, by The Boeing Commercial Airplane Company. This study, referred to as Phase II, was conducted in the period from January 1974 to June of 1975. It was an extension of a previous Phase I study contract which is summarized in a final report "Advanced Supersonic Propulsion Study" – NASA CR-134633.

The NASA project manager for this study contract was Dr. Edward A. Willis, Flight Performance Office, Lewis Research Center, Cleveland, Ohio. Key P&WA personnel were Robert A. Howlett, Study Program Manager, George A. Aronstamm, Jack W. Johnson and Joseph Sabatella. Key Boeing personnel were Lowell D. Richmond, Program Manager, George Evelyn and Gary Klees.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF TABLES

LIST OF TABLES (Cont'd)

LIST OF TABLES (Cont'd)

SUMMARY

NASA is engaged in a study of the application of advanced technology to long-range, supersonic, commercial transport aircraft with emphasis on reduced noise and emissions and improved economics. As part of this program, P&WA has been conducting advanced supersonic propulsion studies under contract NAS 3-16948. The overall objective of this study is to identify advanced engine concepts and related technology programs necessary to provide a sound basis for design and possible development of an advanced supersonic propulsion system. Phase I of this study was completed in 1973 and results were reported in NASA CR-134633 – Advanced Supersonic Propulsion Study – P&WA's Final Report. Phase II was conducted through 1974 and into 1975 and is the subject of this final report. This P&WA study is continuing in an on-going NASA contract, NAS 3-19540. As these studies progress, the most promising engine concepts are refined and improved, while the less attractive concepts are screened and eliminated.

In Phase I of these Advanced Supersonic Technology (AST) propulsion studies, a broad spectrum of conventional and unconventional propulsion systems were studied over a wide range of cycle variables. From this initial phase, it was concluded that noise constraints have major impact on the various engine types and cycle parameters being evaluated. The duct-heating turbofan with a low level of jet suppression in the bypass stream was identified as the most attractive engine for the noise level from FAR 36 down to minus 5 EPNdB. The series/parallel Variable Cycle Engine (VCE) concept was also found to be competitive and was considered to have the potential of possibly lower noise levels with moderate penalties to the overall system. This Phase I study also showed that an advanced supersonic commercial transport would benefit appreciably from the application of advanced engine technology projected for certification by the late 1980's or early 1990's.

Phase II was a more concentrated parametric study including refined cycle studies, airplane integration studies conducted jointly by P&WA and Boeing, and initiation of preliminary design for selected engines. The two most promising engine concepts identified in Phase II were the Variable Stream Control Engine (VSCE) and a single rear-value VCE concept. These engines evolved in the Phase II refinement studies by building on the Phase I engine concepts.

Both of these VCE concepts feature independent temperature and velocity control for two coannular nozzle exhaust streams. This flexibility, in combination with the use of variable geometry components, provides excellent flow matching capability between the inlet and the engine over the entire flight spectrum, as well as reductions in jet noise. The resulting improvements in installed performance and lower noise levels provide significant benefits to the overall supersonic transport relative to current technology designs. The on-going Phase III study will continue to refine and compare these two concepts, as well as evaluate additional unconventional engine concepts.

One of the most promising improvements for these VCE concepts is a potential noise benefit associated with two-stream coannular nozzles. This potential benefit may eliminate the need for mechanical jet noise suppressors which could cause significant penalties to these engines and to the overall system. If further evaluation of this coannular noise benefit indicates these engines do require suppressors, they would be applied to the outer exhaust stream only, thereby simplifying the suppressor design and reducing the associated penalties. Based on this jet noise improvement plus additional advanced technology features, the Phase II study results indicate these VCE concepts may reduce sideline jet noise by approximately 10 EPNdB relative to current technology supersonic engines. In addition, they have the potential to improve the economic characteristics of supersonic transports by significant reductions in the airplane design size for a fixed payload, or by increasing the design range. The improvements projected for these advanced engines are based on several critical technology requirements, including: a high performance nozzle with low jet noise; primary and duct-burner configurations designed for low emissions; variable geometry components including a near-sonic inlet for noise control, a variable fan, and variable area nozzles; high temperature materials and cooling systems for the hot sections of these engines; an integrated electronic control system; and numerous features associated with integrated propulsion systems. Programs are recommended in Section 4.0 of this Final Report for each of these critical technology areas.

CONCLUSIONS AND RECOMMENDATIONS

GENERAL PROGRESS

Significant progress has been made in the Phase II parametric variable cycle engine refinement and integration studies.

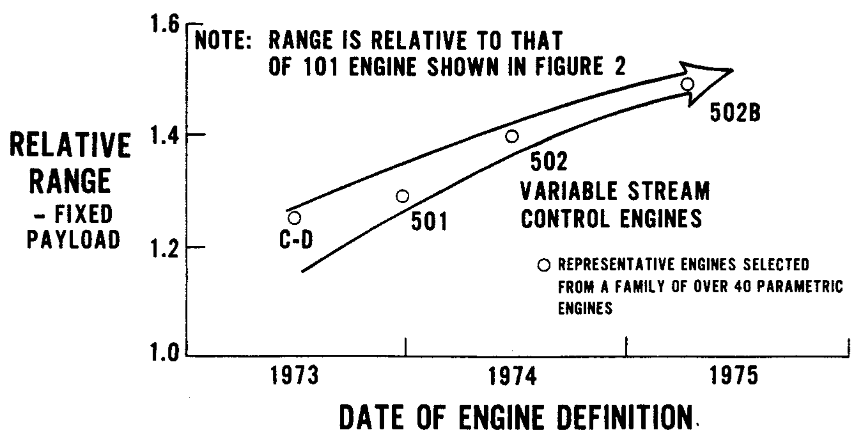
Typical progress is shown in Figure 1 for several representative Variable Stream Control Engine (VSCE) concepts. In this curve, the evolution of VSCE concepts is plotted in terms of relative airplane design range versus the date when the engine was defined. This VSCE concept was derived from the duct-heating turbofan engine defined parametrically in the Phase I study. For comparison with other engine concepts, the range in Figure 1 has been normalized relative to the VCE-101 engine concept shown in Figure 2. Each engine in these figures is sized to meet FAR Part 36 sideline jet noise levels without jet noise suppressors. Also, all of these engine definitions are based on consistent levels of advanced technology. Figure 1 indicates that the best VSCE concept (502B) resulted in a 20% improvement over the Phase I engine (C-D).

Figure 2 shows the progress made for several representative valved Variable Cycle Engine (VCE) concepts. In this curve, the evolution of valved VCE concepts is shown as a range improvement relative to a representative single front-valve definition (VCE 101 from the Phase I parametric study). This is the same reference engine used in Figure 1. As shown in Figure 2, the best VCE concept evaluated in this Phase II study is the single rear-valve VCE (112B), and has a 40% range improvement over the Phase I valved engine concept.

A range comparison of the two most promising VCE's is shown in Figure 3. This curve combines Figures 1 and 2, and shows the relative range comparison for these engine concepts at the completion of this Phase II study. This comparison is somewhat premature in that the rear-valve VCE concept, because it was defined late in this study, has not received the level of parametric study and the same degree of refinement that the VSCE concept has. Both of these VCE concepts will be evaluated further in the follow-on Phase III propulsion system studies.

POTENTIAL IMPROVEMENTS RELATIVE TO CURRENT TECHNOLOGY ENGINES

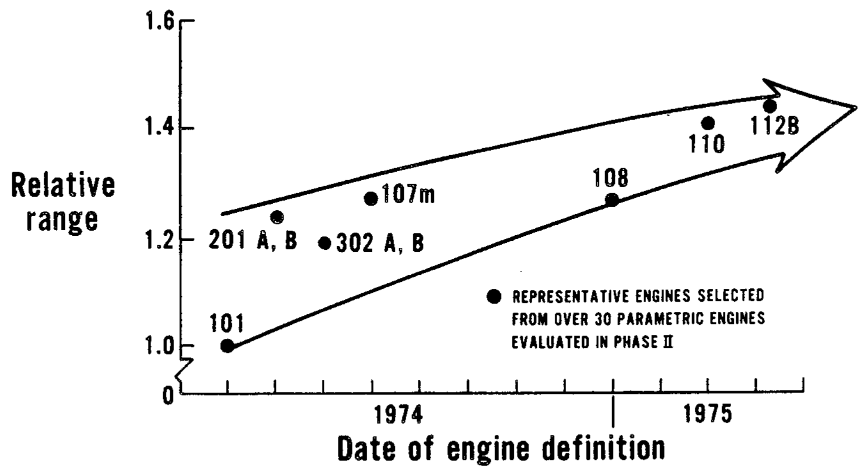
One of the most promising improvements for these Variable Cycle Engines is a potential jet noise benefit associated with two-stream coannular nozzles. P&WA has conducted a test program under NASA sponsorship (NAS3-17866) to evaluate the jet noise characteristics of coannular nozzles with and without jet noise suppressors. Static test data indicates a significant reduction in jet noise (7 to 9 EPNdB) for unsuppressed coannular nozzles which have a velocity profile of the type shown in Figure 4. This noise benefit is a result of a mixing and momentum exchange process of the high velocity bypass stream with ambient air along the outer surface and with the lower velocity primary stream along the inner surface. With the relatively small height of the bypass stream, mixing of the high velocity stream with ejector air and with the lower velocity engine stream is readily accomplished. The net effect is equivalent to an increase in bypass ratio and a lower jet velocity for the bypass stream, resulting in reduced jet noise. This potential jet noise benefit may eliminate the need for mechanical jet noise suppressors which could cause significant penalties in terms of weight, performance and overall complexity to the nozzle and reverser system. If a suppressor is required, by using the same velocity profile shown in Figure 4, it would only have to be applied to the bypass stream. Penetration of the engine stream is not required. This yields a much simpler suppressor design, with an attendant reduction in weight and performance penalties. The next phase in evaluating this potential coannular jet noise benefit is to determine the noise and performance characteristics at conditions that simulate take-off flight velocities. Work has been initiated on this next phase and results are expected to be available during the first quarter of 1976.



CODE FOR VARIABLE STREAM CONTROL ENGINES SHOWN IN FIGURE 1

Number	Type	Reference
C-D	Duct-Heating Turbofan	Best engine from Phase I parametric studies
501*	Preliminary VSCE Concept	First derivative of C-D engine
502*	Improved VSCE Concept With Inverse Throttle Schedule	Parametric engine
502 B*	VSCE with Higher Flow Schedule and Improved Duct-Burner	Refined engine

Figure 1 *Evolution of Variable Stream Control Engine Concept*



CODE FOR VALVED VARIABLE CYCLE ENGINES SHOWN IN FIGURE 2

Number	Type	Reference
101	Single Front-Valve	Representative engine selected from Phase I parametric studies
107M*	Single Front-Valve	Refined for High Flow Capability at Supersonic Cruise
108	Single Front-Valve	Refined for Reduced Weight
201A*	Dual-Valve With Augmentor	Parametric Engine
201B*	Dual-Valve With Augmentor	Parametric Engine with high-flow capability for supersonic operation
302A	Dual-Valve - No Augmentor	Parametric Engine
302B*	Dual-Valve - No Augmentor	Parametric Engine with high-flow capability for supersonic operation
110	Single Rear-Valve	Parametric Engine derived from other valved engines and from Variable Stream Control Engine
112B*	Single Rear-Valve	Improved Engine from Parametric Study

*Issued as a data-pack engine for NASA SCAR airframe contractor evaluation

Figure 2 Evolution of Valved Variable Cycle Engines

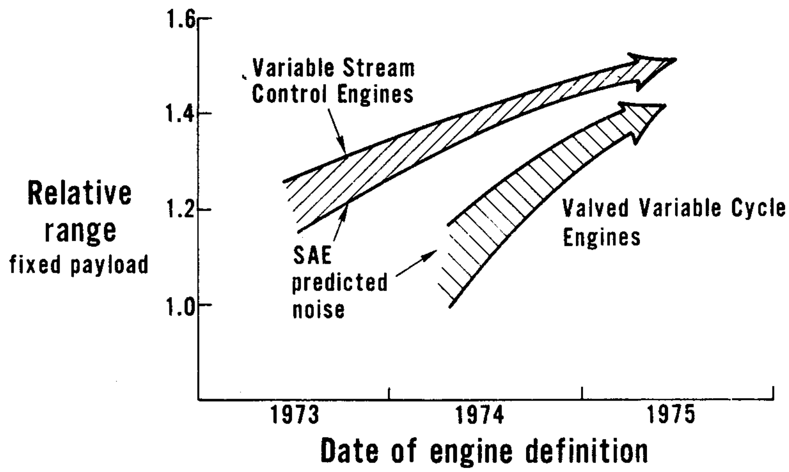


Figure 3 *Comparison of Variable Cycle Engines*

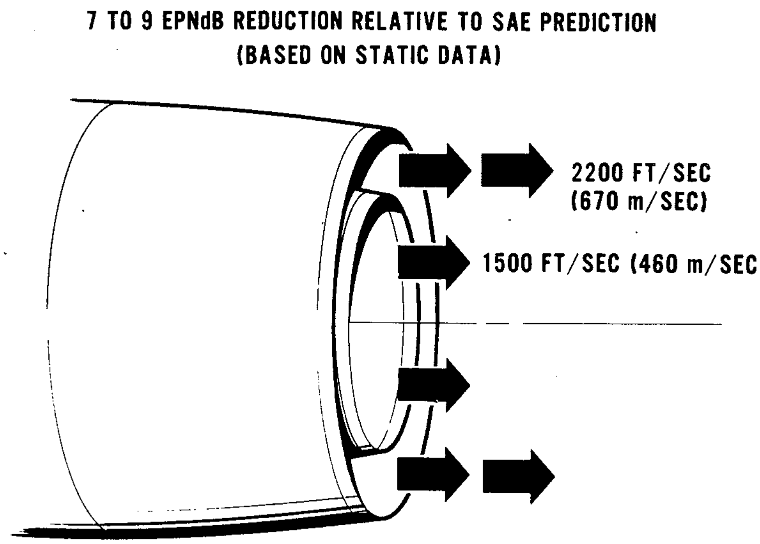


Figure 4 *Coannular Nozzle Velocity Profile*

Applying this potential noise benefit of coannular nozzles to the VSCE concept, the relative range is improved another 10% as shown in Figure 5. This improvement is brought about by being able to scale the engine to a smaller size while holding jet noise constant. As shown by the slope of the top arrow, the coannular noise benefit is more potent for the 502B engine than for the 502. This is because the performance improvements in the refined B engine enable it to be sized for a smaller airflow. The coannular noise benefit enhances the performance of the 502B engine so that a smaller size is more optimum for both FAR Part 36 jet noise and installed performance. Expressing this potential noise benefit in terms of reduction in jet noise, Figure 6 compares 90 EPNdB noise contours for the VSCE-502 engine during take-off. Each of the three noise contours in this figure is for a fixed engine and airplane size (constant Take-off Gross Weight [TOGW]). The top curve shows the contour corresponding to full-power take-off without suppression of any type and without the coannular benefit. This contour was estimated by applying the SAE jet noise prediction procedure. The middle curve is for the same power setting but adjusted for the coannular noise benefit based on static test data. The contour area is reduced to one-third. The bottom curve shows a further reduction to one-fourth the area. This is provided by the coannular noise benefit combined with power cut-back during climb-out to reduce community noise. In concept, this noise benefit can be applied to the rear-valve VCE as well as the VSCE. However, when the inverse velocity profile shown in Figure 4 is applied to the high core flow of the rear-valve VCE, the reduction in specific thrust may require oversizing this engine. Evaluation of this noise benefit for the rear-valve engine concept will be conducted in the Phase III follow-on propulsion system study.

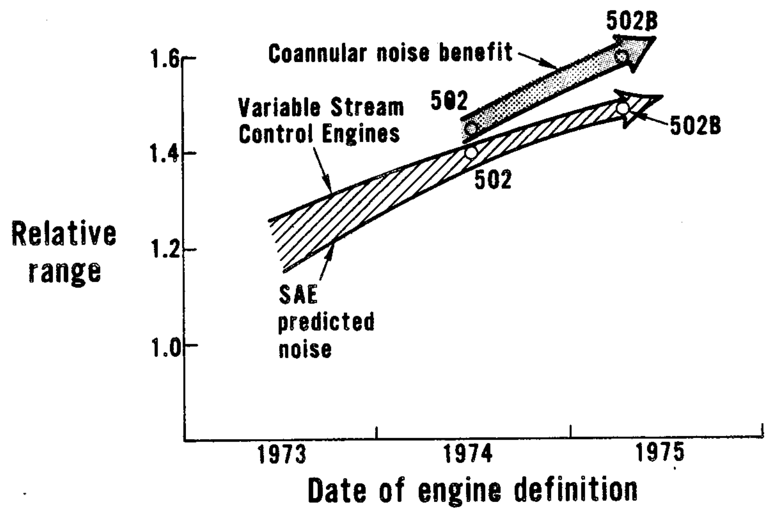


Figure 5 *Potential Benefit of Coannular Nozzles*

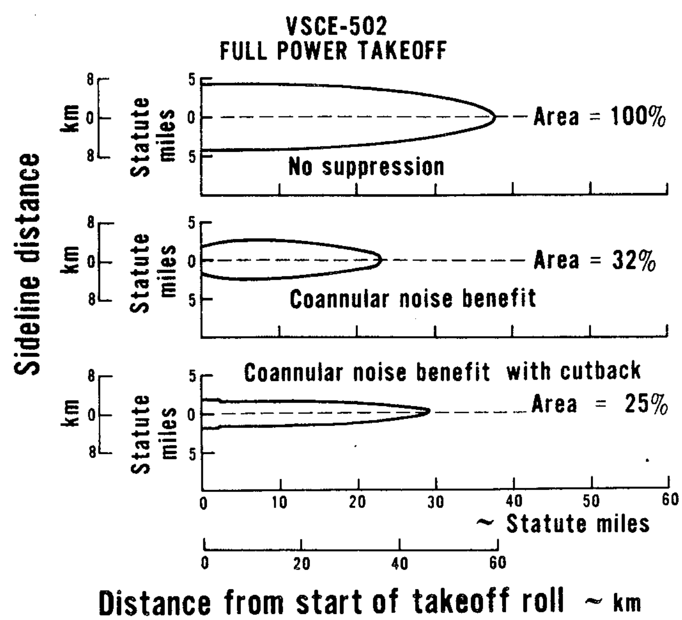


Figure 6 *90 EPNdB Footprint Contours for VSCE-502*

As an indication of the overall potential improvements provided by these advanced VCE's relative to current technology 1st generation SST engines, Figure 7 shows a curve of TOGW vs. sideline noise. The data in this curve is based on a fixed level of airplane technology and shows the impact when going from current technology unsuppressed engines to the advanced technology VCE's with the coannular noise benefit. The potential benefit is expressed in Figure 7 as a 20% reduction in TOGW and an 8 EPNdB reduction in sideline jet noise.

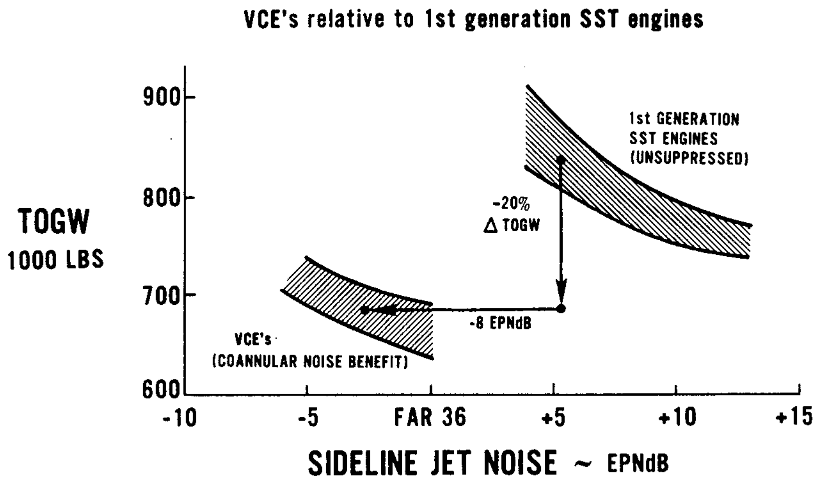


Figure 7 *Potential Improvements of Variable Cycle Engines Over First-Generation SST Engines*

Another assessment of the potential benefit from these advanced VCE's is shown in Figure 8. This curve includes advanced supersonic airplane technology (aerodynamic, structural and materials) in addition to the advanced VCE concepts. Relative total operating cost is plotted vs. noise level for 1st generation SST's, advanced supersonic transports with VCE's, and current wide-body subsonic transports. A 40% reduction in total operating cost plus a 10 to 13 EPNdB reduction in jet noise level is projected for advanced supersonic transports relative to 1st generation SST's. As indicated, the benefits of supersonic flight may be obtained with the same noise characteristics as current wide-body transports, and with only slightly higher total operating costs.

MOST PROMISING ENGINES

Cycle, weight and dimensional characteristics of the two most promising VCE concepts are listed in Table I. Figure 9 shows a flowpath of the Variable Stream Control Engine (VSCE-502B) and Figure 10 shows the rear-valve Variable Cycle Engine (VCE-112B).

TABLE I

CHARACTERISTICS OF THE MOST PROMISING PHASE II ENGINES

	Variable Stream Control Engine (VSCE-502B)	Rear-Valve Variable Cycle Engine (VCE-112B)
Fan Pressure Ratio	3.3	5.8
Bypass Ratio	1.3	2.5
Overall Pressure Ratio	20:1	25:1
Total Corrected Airflow ~lb/sec	900	900
(kg/sec)	(405)	(405)
Maximum Combustor Exit Temperature		
Primary Burner ~°F	2800	2800
(°C)	(1540)	(1540)
Duct Burner ~°F	2500	1900
(°C)	(1370)	(1040)
Engine Weight lb	10500	11450
(kg)	(4750)	(5200)
Engine and Nozzle/Reverser Weight lb	13400	13500
(kg)	(6200)	(6300)
Overall Length of Engine and Nozzle ~in	266	305
(m)	(6.80)	(7.70)
Maximum Diameter ~in	88	82
(m)	(2.23)	(2.08)

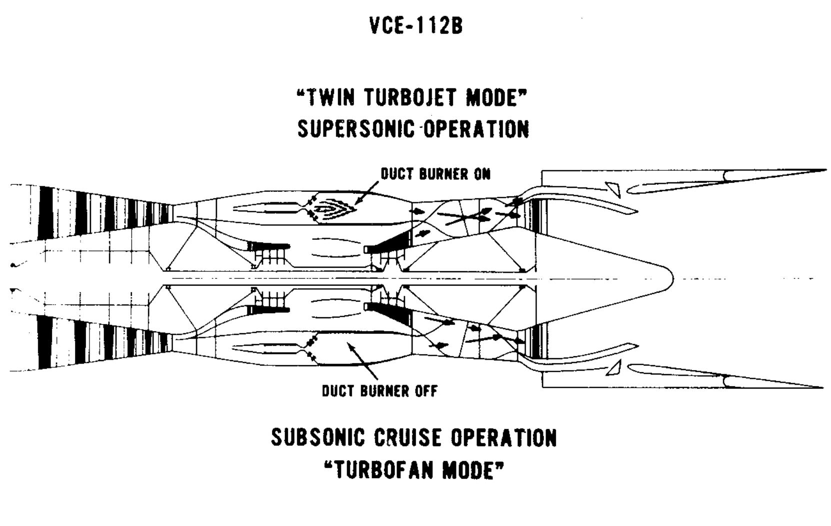


Figure 10 VCE-112B Rear-Valve Variable Cycle Engine

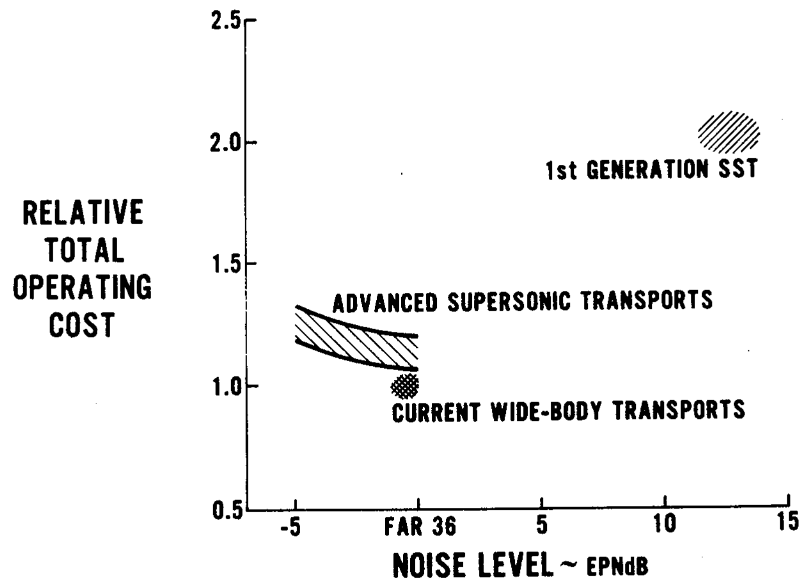


Figure 8 *Potential Impact of Advanced Supersonic Technology on Economics and Noise*

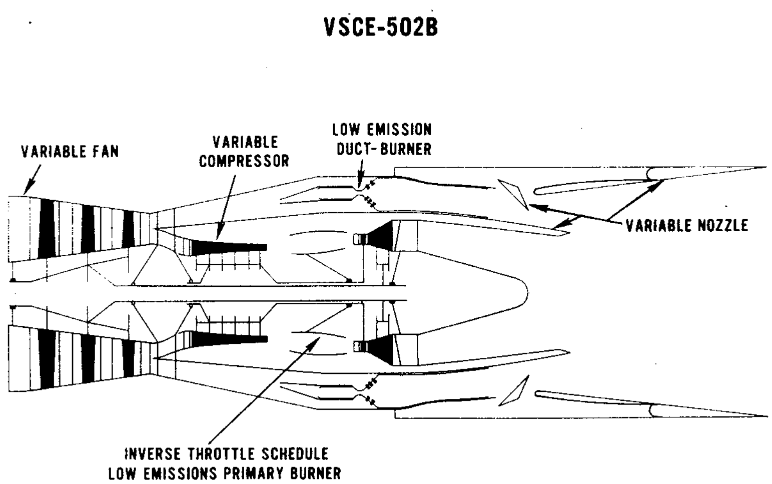


Figure 9 *VSCE-502B Variable Stream Control Engine*

Some key features of the VSCE-502B concept are:

- Variable geometry components provide the operating flexibility for low noise operation as well as high performance for subsonic and supersonic cruise.

- An inverse throttle schedule control for the main burner and a compatible control schedule for the duct-burner provides the operating flexibility to meet take-off noise levels and to provide low TSFC at subsonic and supersonic cruise.

- The reoptimized cycle with reduced bypass ratio gives improved supersonic TSFC by reducing the level of augmentation required for supersonic cruise.

- Incorporation of high performance coannular nozzles offer a potential noise benefit when the bypass stream has a higher velocity than the core engine stream.

- Main burner and duct-burner configurations based on experimental combustor concepts tested in the NASA/Pratt & Whitney Aircraft Experimental Clean Combustor Program (NAS3-16829) reduce engine exhaust emissions.

- The high-performance nozzle system is integrated with a targetable thrust reverse.

- Advanced materials are incorporated throughout the engines, especially in the engine hot section.

- A structural nacelle provides independent support for the inlet, engine, nozzle and reverser systems.

Some key features of the rear-valve VCE-112B concept are listed below. In addition, this valved engine also incorporates most of the key features listed for the VSCE-502B.

- This engine has two modes of operation: (1) the "twin turbojet" mode which is achieved by using the rear valve to invert the two streams when the duct-burner is operating and (2) the "turbofan" mode which is used for part-power operation such as subsonic cruise when the duct-burner is not operating. In the "turbofan" mode, the rear valve mixes the two engine streams and passes them through the rear turbine. This preserves the airflow match in the rear turbine and yields high turbine efficiency for part-power subsonic cruise operation.

- The "twin turbojet" mode can be accomplished with only one valve. This capability previously existed only in the heavier dual-valve VCE's.

- Total engine airflow is not affected by the rear-valve position as it is by the valve position in front-valve VCE concepts. Climb airflow and thrust are therefore not reduced when the engine is switched to the "twin turbojet" mode of operation.

- At takeoff, the engine achieves low jet velocities by operating in the intermediate temperature (1900°F duct-burner exit temperature) "twin turbojet" mode. The primary burner can be throttled independently to balance the jet noise between the coannular streams.

- Locating the duct-burner ahead of the valve results in a decreased engine length (relative to the dual-valve VCE configurations).

- The high bypass ratio (2.5) reduces the gas generator weight to help offset the weight of the valve and rear turbine assembly.

- The duct-burner thrust efficiency is high because the temperature profile is flattened due to attenuation as the profile passes through the valve and rear turbine assembly.

- The supersonic TSFC and thrust characteristics of this rear-valve VCE are similar to a turbojet – they both have relatively flat TSFC characteristics over a range of thrust levels.

OTHER ENGINES

Other engines studied in Phase II were dual-valve VCE concepts, single front-valve concepts, and Low Bypass Engines (LBE's), with and without afterburning.

None of the dual-valve VCE Concepts evaluated in Phase II is competitive, primarily because of their inherent complexity and excessive weights. These penalties offset the supersonic TSFC advantage of these dual-valve concepts which is provided by converting to the turbojet cycle. No further evaluation of dual-valve VCE's is recommended for advanced supersonic transports. This recommendation is based on the extensive parametric studies and on the optimistic projections of unique technologies for these dual-valve engines.

Single front-valve VCE concepts cannot provide sufficient variation in bypass ratio to improve supersonic TSFC and still retain the advantages of turbofan engines, especially their low weight and low noise. All of the front-valve VCE concepts suffer from a 30% or more reduction in total engine air flow when shifting from the high to the low bypass mode. This shift occurs when going from subsonic to transonic climb. The thrust loss resulting from this airflow reduction causes an extended climb time and related penalties in TSFC during climb and at supersonic cruise. The potential benefit of redefining these engines for higher airflow schedules for supersonic operation was investigated. The weight penalties associated with high-flowing were found to offset the performance gain. It should be noted that the rear-valve VCE-112B concept was defined to overcome the disadvantages related with this flow reduction. No further evaluation of single front-valve VCE's is recommended for advanced supersonic transports.

Low bypass ratio (<0.5), mixed-flow turbojet engines have approximately the same supersonic TSFC levels as the most promising VCE concepts. However, the high weight and poor subsonic TSFC characteristics, plus the dependence of these engines on high levels of jet noise suppression, make the turbojet family of engines less competitive than the VSCE and VCE concepts.

CRITICAL TECHNOLOGY REQUIREMENTS

Critical technology requirements that are common to the two most promising Variable Cycle Engines are:

- Low noise, high performance coannular nozzle*
- Low emissions duct-burner*
- Variable geometry multi-stage fan*
- Low emissions primary burner
- Hot section technology
  - Directionally solidified eutectic blades
  - Ceramic vanes, endwalls and tip seals
  - High creep strength disk material
  - Active tip clearance control system
  - Oxide dispersion strengthened burner liner materials
- Full-authority electronic control system
- Variable geometry low-noise inlet
- Propulsion system integration features

Additional critical technology requirements that are unique for the rear-valve VCE concepts are:

- Rear Flow Inverter Valve
- Rear Turbine
- Nozzle/Ejector System

*Emphasis on unique technologies

RECOMMENDATIONS

Recommendations for further studies and technology programs:

- Continue Propulsion System Studies, concentrating on further refinement and preliminary design studies of the most promising Variable Cycle Engines

- Continue Joint Engine/Airframe Integration Studies for the most promising engine concepts. These integration studies should focus on structural nacelle concepts, inlet/engine aerodynamic compatibility, nozzle and reverser systems, thermal management, advanced accessories and drive systems, and an integrated engine/airplane electronic control system

- Continue or start research and technology programs for the most critical propulsion system requirements

- Start planning a Variable Cycle Engine demonstrator program. A building-block approach is considered to be most effective as this will allow each critical technology to be demonstrated in an engine as individual research and technology programs provide the foundation for the design of each unique component.

1.0 INTRODUCTION

The National Aeronautics and Space Administration (NASA) is engaged in a study of the application of advanced technology to long-range, supersonic, commercial transport aircraft with emphasis on reduced noise and emissions and improved economics. The NASA Langley Research Center is conducting an overall Supersonic Cruise Airplane Research (SCAR) Program. In parallel, the NASA Lewis Research Center is conducting Advanced Supersonic Technology (AST) Propulsion Studies and technology programs. As part of this overall program, P&WA has been conducting advanced supersonic propulsion studies under contract NAS3-16948. The overall objective of this study contract is to identify technology programs necessary to provide a sound basis for design and possible development of an advanced supersonic propulsion system. This information will be needed to permit sound judgement if a decision is eventually to be made to proceed with an advanced supersonic transport.

1.1 BACKGROUND

In Phase I of these AST propulsion studies[(1)*], a broad spectrum of conventional and unconventional propulsion systems were studied over a wide range of cycle variables. The conventional engines included the non-afterburning turbojet, the afterburning turbojet, the duct-heating turbofan and the afterburning turbofan. The unconventional engines included variable cycle concepts of the series/parallel type which provide the capability to vary bypass ratio, the augmented wing concept, the auxiliary engine concept, and the turbofan ramjet. Two technology levels were projected and evaluated: 1975 and 1980 technology. These technology levels were defined as engine component technology that can be demonstrated by the indicated time period and then committed to an engine development program for certification by the late 1980's or early 1990's.

The P&WA Phase I Study showed that noise constraints have a major impact on the selection of the various engine types and cycle parameters. Several promising advanced propulsion systems were identified as having the potential of achieving low noise levels and emissions with better system economics than the first generation SST systems. The non-afterburning turbojet, utilizing a high level of jet noise suppression, was determined to be a competitive engine around the FAR 36 noise level. The duct-heating turbofan with a low level of jet suppression in the bypass stream was the most attractive engine for the noise level from FAR 36 down to minus 5 EPNdB. The series/parallel Variable Cycle Engine concept was competitive in this same noise range and was considered to have the potential of possibly lower noise levels with moderate penalties. Afterburning turbofans were found to have TSFC and weight penalties that were significantly higher than the other types of engines. They were, therefore, eliminated as candidate AST engines.

This Phase I study also showed that an advanced supersonic commercial transport would benefit appreciably from the application of advanced engine technology. These benefits can be realized in terms of improved system economics, lower noise levels, and reduced emissions. In addition to recommending research and technology programs in several critical engine component areas, the Phase I study was concluded with the recommendation that

*Numbers in parenthesis refer to references listed in List of References on Page No. 193.

the evaluation and comparison of the most promising engine concepts be continued. These study recommendations emphasized the need for integrated airplane propulsion system evaluation as well as refined parametric studies and preliminary design of the most promising selected engines.

In parallel with this P&WA Phase I study, Boeing had conducted preliminary definition and evaluation studies of unconventional engine concepts which incorporated a unique flow control valve, called an Annulus Inverting Valve (AIV) to change the bypass ratio of an engine. Preliminary Boeing assessment of these engine concepts, called Multi-Cycle Engines (MCE's), were found to provide significant potential improvements in airplane design range and off-design performance characteristics relative to conventional technology engines. NASA awarded P&WA a contract to continue the AST propulsion studies including the refinement of these single- and dual-valve MCE concepts defined by Boeing. P&WA subcontracted a portion of this follow-on study to Boeing to conduct parametric airplane integration studies of these unconventional engine concepts.

While Phase I consisted of broad parametric studies of a wide variety of engine concepts, the follow-on contract, herein referred to as Phase II, was a more concentrated parametric study including refined cycle studies, airplane integration studies and initiation of preliminary design of the most promising engines.

1.2 DESCRIPTION OF PHASE II STUDY TASKS

The results of the P&WA Phase I AST propulsion study and the Boeing definition of Multi-Cycle Engine Concepts provided the initial input to the Phase II study program. The specific objectives of Phase II were to define, evaluate and compare conventional and Variable Cycle Engine (VCE) concepts with emphasis on environmental characteristics (noise and emissions) and economic factors (TSFC, TOGW, DOC and ROI); provide engine definition to NASA and the airframe contractors involved in the SCAR program; conduct parametric airplane/propulsion system integration studies (Boeing was the subcontractor for this integration study); and identify unique critical technology requirements and recommend follow-on programs.

The following Tasks were conducted to meet these program objectives:

Task VII — Concentrated Parametric Studies

Task VII was a concentrated parametric study which provided refined engine definition for the attractive propulsion systems identified in the broad parametric studies of Phase I. This task also extended the unconventional engine studies to include further single and dual-valve Variable Cycle Engine (VCE) configurations. The overall objective of this work was to improve the engine cycles and configurations with respect to performance, noise and emissions. Engine definitions were based on advanced technology projections which were considered appropriate for demonstration by 1980 and could be incorporated in an engine going into operation around the late 1980's or early 1990's. This same level of advanced technology was used for all of the other Phase II Tasks.

Estimates of engine performance, noise, weight and dimensions were made for a variety of cycle parameters for each type of engine. Engine performance and vehicle system screening studies were conducted utilizing this engine data to select the most attractive cycles. For the selected configurations, more complete engine performance and installation data was generated and released to NASA-Lewis, NASA-Langley and associated SCAR airframe contractors in the form of data-packs.

Task VIII – Unique Components

Conceptual design and analysis were conducted in Task VIII for several of the unconventional engine components which were either unique to the candidate propulsion systems being studied or were essential to minimize the pollution and noise characteristics. This conceptual design and analysis work was conducted to establish preliminary feasibility of these unique engine components, to elevate the level of definition of unique components to be closer to that of the more conventional components used in the parametric system studies, and to identify the advanced technology requirements for these unique engine components. The unique components selected for conceptual design and analysis in Task VIII were: flow diverter valves required by the VCE concepts; the third turbine assembly that is a critical component of dual-valve and single rear-valve VCE concepts, engine support and structural concepts for Low Bypass Engines, Variable Stream Control Engines, and valved VCE concepts; and nozzle/reverser/suppressor concepts.

Task IX – Military Application of Variable Cycle Engines

One of the greatest potential benefits of Variable Cycle Engine (VCE) concepts is their flexibility to meet a wide range of operating conditions and varied missions without the off-design penalties associated with conventional engines. The application of VCE concepts developed in the Phase II parametric studies to various military missions was evaluated in conjunction with NASA studies. Because of the restricted nature of this type of evaluation, this report does not include a summary of Task IX.

Task X – Preliminary Design

From the Task VII parametric studies and the Task XIII parametric airplane integration studies, the Variable Stream Control Engine (VSCE) was identified as one of the most promising concepts and was selected for preliminary design in Task X. Because this task was a limited effort, the preliminary design studies concentrated on the unique features of the VSCE. These included a high-pressure turbine disk structural and material evaluation, a review and refinement of the unique component designs to incorporate refined technology definitions, the engine rotor support and bearing arrangements, a maintainability concept, and engine/airplane installation definition.

As Task X preliminary design was being conducted, the Task XIII integration studies were also in progress to improve and refine valved VCE concepts. Late in Phase II, the single rear-valve VCE configuration was identified as the best valved engine concept evaluated in these studies. Further evaluation and refinement of this rear-valve VCE concept are planned for the follow-on Phase III study contract, including the possibility of a preliminary design effort, along with the continuation of the VSCE preliminary design studies.

Task XI — Critical Technology Requirements and Program Recommendations

Realization of the environmental and economic improvements that are described in this report is contingent on substantial research and technology programs in several critical areas. In Task XI, critical technology requirements were identified for the most promising engine concepts. Also, program recommendations were made to continue or initiate research and study programs in these critical areas.

Task XII — Technology Comparison

The most promising AST engine concepts defined in Phase II were compared with first generation supersonic transport engine configurations in Task XI. The purpose of this task was to identify the technology required by the candidate AST engines to reduce noise and emission levels and to improve system economics. Because of the proprietary nature of these technology comparisons, this final report does not contain the results from Task XII.

TASK XIII — Parametric Airplane/Propulsion System Integration and Variable Cycle Engine Refinement Studies

This task evaluated in a parametric manner the broad influence that the airframe and nacelle designs have on the desirable features of the most promising engine concepts. Candidate engine concepts were identified, the effects of major perturbations in the mission and in the design of the engine and airframe were evaluated and potential performance benefits of VCE's were determined by comparison with conventional engine cycles. Boeing supported this study task in a subcontractor role.

Vehicle system and mission groundrules were established which permitted the evaluation of data pack engines in a consistent manner in order to identify the propulsion systems that have the greatest potential to reduce noise and combustion emission levels and also to provide improved characteristics for the overall airplane system. Results from these integration studies led to the selection of two engine configurations for refined definition and further integration studies: the Variable Stream Control Engine (VSCE) and the single rear-valve Variable Cycle Engine (VCE). The rear-valve VCE concept combines the best features of the Variable Stream Control Engine and the dual-valve VCE concept. Refinement studies were conducted to improve the cycle and inlet/engine matching characteristics and the mechanical and aerodynamic configuration of these two selected engines. Engine performance and installation data were generated and released to NASA and associated SCAR airframe contractors in the form of data packs for these two refined engines. Vehicle system integration studies were conducted by Boeing and P&WA including refined pod definitions, vehicle system performance, emissions and noise estimates.

In addition to the vehicle system evaluation of these engine configurations, the system sensitivity to perturbations in the mission, airframe and engine designs was evaluated. These studies included the effect of take-off field length, supersonic cruise Mach number, different vehicle plan forms such as the delta wing and the arrow wing/blended body aircraft and propulsion system pod shapes and locations.

2.0 STUDY PROCEDURE

The interrelationship of the seven Phase II tasks described in the Introduction (Section 1.0) is shown schematically in Figure 2-1. Also shown is the relation of the Phase II study to Phase I and to the follow-on Phase III study effort. The broad parametric studies of Phase I provided the foundation for the more detailed studies in Phase II. Likewise, Phase III will include further refinement and system integration studies based on the results of the Phase II studies.

As shown in Figure 2-1, Tasks VII through XIII were not independent tasks but supported each other. The effort under Task VII, which consisted of screening and detailed parametric studies of the most promising Phase I engines plus additional concept definitions, provided input to the design studies (Tasks VIII and X) as well as input for the formulation of data-packs which were provided to NASA and related SCAR airframe contractors. Task VII also provided the basis for the Task IX engine definitions (Military Applications) and for Task XIII (the Airplane Integration studies). The design tasks (VIII and X) along with Tasks IX, XII and XIII provided the basis for Task XI (identification of critical technology requirements and related program recommendations).

The various study methods and groundrules employed in the Phase II study will be outlined in this section. The study procedures used in this program were not task dependent but were generally used throughout the total study effort, the format of this procedural section is by study discipline rather than by study task. Since the vehicle systems study procedures used by P&WA and Boeing varied slightly, both are presented.

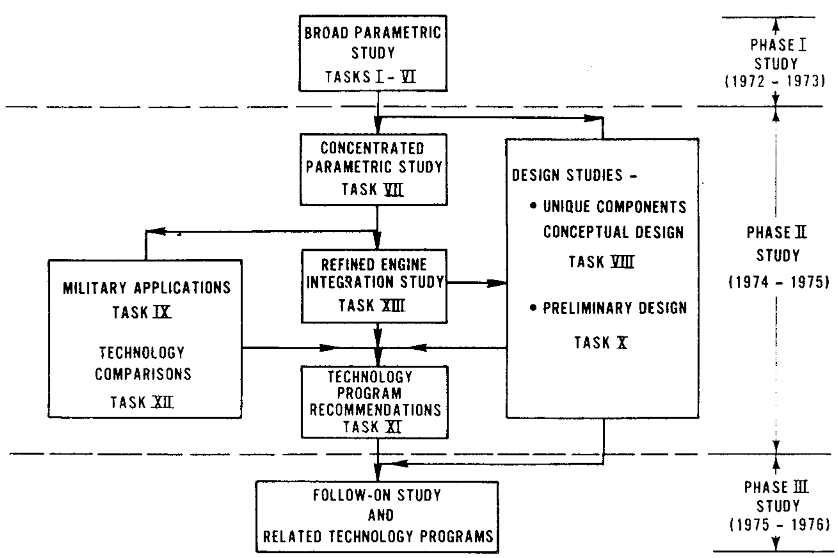


Figure 2-1 Interrelationship of Propulsion Study Tasks

2.1 GROUNDRULES

The groundrules for the Phase II study were defined by NASA-Lewis after discussions with NASA-Langley and the airframe and engine contractors. Figure 2-2 is a listing of the groundrule parameters. As shown in this figure, the evaluations covered a range of engine, airplane and environmental parameters.

AIRPLANE DESIGN	MODIFIED ARROW WING (LANGLEY REFERENCE AIRPLANE) AND MODIFIED DELTA WING
FLIGHT MACH NO.	2.2, <u>2.4</u>, 2.7
TAKEOFF FIELD LENGTH	10,500 TO 12,400 FT
NOISE LEVEL	FAR PART 36 TO -10 EPNdB
FUEL RESERVES	LOCKHEED/TWA MODIFIED
PAYLOAD	292 PASSENGERS/61,030 LBS
INLET CONFIGURATION	AXISYMMETRIC
TOGW	VARIABLE
DESIGN RANGE	4,000 N. MI.
DESIGN MISSION PROFILES	NOMINAL - ALL SUPERSONIC ALTERNATE - MIXED WITH 600 N. MI. SUBSONIC CRUISE
ECONOMIC EVALUATION	BASED ON 2500 N.MI. AVG MISSION INCLUDING 400 N. MI. SUBSONIC CRUISE LEG
ENGINE TECHNOLOGY	FOR CERTIFICATION IN THE LATE 1980'S

Figure 2-2 *AST Study Ground Rules*

2.2 P&WA STUDY PROCEDURES

2.2.1 Technology Projections

Engine component configuration and performance definitions were based on propulsion system technology projections which were considered appropriate for 1980 and could lead to operational capability for commercial engines in the late 1980's to early 1990's. The technology projections included engine materials, component aerodynamic loadings, component performance (efficiencies and pressure losses), mechanical arrangements, and unique component definitions. These component technology projections provided the basis for defining the various types of engines including performance, dimensions, and weight estimates necessary to evaluate each engine concept. Section 3.1.2 summarizes these technology projections.

2.2.2 Engine Performance

Engine performance was estimated for a range of cycle parameters for each type of conventional and unconventional engine concept. These estimates incorporated the component performance based on the advanced technology projections.

Cycle studies were conducted to compliment Phase I parametric studies in order to select specific engine cycles for further study in Phase II. Each type of engine concept was evaluated with respect to changes in cycle parameters such as bypass ratio, fan pressure ratio, overall pressure ratio and burner temperature schedules. Each type of engine was screened based on engine performance and estimated system characteristics (TOGW and jet noise). For each concept, the combination of cycle parameters was selected to produce the best performance with minimum sideline jet noise. For engines with separate nozzle streams (VSCE's and valved VCE's), this was achieved by balancing the primary and duct stream jet velocities. The mixed-flow Low Bypass Engines (LBE) were defined with the additional requirement of a static pressure balance between the primary and bypass streams.

The engine concepts were evaluated for Mn 2.4 supersonic cruise operation, which represents an intermediate Mach number between the Mn 2.2 to 2.7 supersonic cruise range being evaluated. Baseline inlet characteristics, including airflow schedule and pressure recovery, assumed for this study were those of a representative Mn 2.4 inlet. This inlet is an axisymmetric, mixed compression, variable geometry configuration. Selected engine cycles were also evaluated for the impact of different inlet airflow schedule on engine performance and system characteristics.

The method used to determine nozzle performance accounted for the most important internal and external nozzle performance parameters. The aerodynamic characteristics of the exhause nozzle were approximated by using a computerized procedure which trades internal nozzle performance against external drag to produce the best overall performance. Internal nozzle performance includes such effects as flow profile, internal friction, shock and divergence losses. External drag includes the effect of nozzle boattail angle only. Selection of the appropriate nozzle geometry, such as the flap lengths, areas and angles, was based on preliminary nozzle design layouts. These layouts emphasized the basic nozzle requirements of a supersonic transport system; supersonic and subsonic TSFC, jet noise and thrust reversal.

In order to optimize engine performance between the subsonic and supersonic cruise conditions and to minimize jet noise at take-off, the effect of engine throttle schedules and variable geometry was evaluated. The variable geometry included variable fan stators, variable high-pressure compressor stators, variable turbine vanes and variable exhaust nozzles.

2.2.3 Engine Dimensions and Weight

An engine configuration was established for each of the selected cycles evaluated in the systems studies. This engine configuration provided engine dimensions and was used as the basis for weight estimates.

Engine configurations were defined by constructing an engine flowpath consisting of the various engine components. Each engine component, such as the compressor, burner, turbine, etc., was configured for consistency with the cycle characteristics (i.e., pressure ratio, airflow, etc.) and the advanced technology projections for that particular component. This resulted in a component definition which included such items as the number of stages, component lengths and diameters, materials, rotor speeds, diffuser lengths, combustion lengths, valve diameters and lengths, and engine support arrangements.

The engine weight estimating procedure utilized in this study consisted of a component by component weight estimate. The weight for each engine component was estimated based on the component flowpath definition, the advanced materials, temperatures, pressures and stress levels. This procedure is superior to alternate techniques, such as overall engine weight correlations with cycle parameters, since it accounts for specific dimensions, rotor speeds, pressures, temperatures, materials and technology for each unique component for each engine configuration.

An engine installation drawing was generated for the configurations selected for data pack definition. The installation drawing provided the engine and case dimensions, engine mounts, engine center of gravity, accessories and tower shaft location. This drawing was based on the flowpath definition, nozzle area requirements and actuation and control systems requirements.

Dimension and weight scaling data were also provided to permit scaling the engine to sizes other than the base definition which corresponded to a total engine airflow of 900 lb/sec (408 kg/sec).

2.2.4 Noise

Jet noise has been identified as the dominant noise problem of the first generation, conventional SST engines. In this Phase II study, preliminary screening and the comparison of parametric engines were made on the basis of sideline jet noise using the SAE AIR 876 estimating procedure, with flight effects allowed for by using relative jet velocity. After the initial screening, a more complete noise analysis was conducted for selected engines representing each type of conventional and unconventional engine.

Jet noise predictions were based on proposed revisions to the SAE AIR 876 procedure dated October, 1973, and an extension of this procedure above 2200 ft/sec (670 m/sec) using P&WA turbojet noise data. This procedure includes: data for estimating jet noise directivity, a variable density correction exponent and a jet temperature effect on jet noise spectra. Although many studies are in progress throughout the aircraft industry to define jet noise flight effects, no accepted prediction procedure is in general use at this time. Therefore, the baseline jet noise calculations summarized in this report were based on relative velocity. To determine the sensitivity of other techniques for calculating flight effects, an alternative procedure [2] for estimating jet noise was evaluated.

Groundrules for the noise estimates calculated for the selected representative engines are:

- All sideline noise estimates were calculated assuming two engines were completely shielded; i.e., only two engines contributed to sideline noise on a four engine aircraft.

- Jet suppressor characteristics assumed in this study were based on DOT-SST static model test results [3]. Suppression levels included the effects of acoustic treatment along the nozzle walls to absorb the high frequency noise generated by the mixing process.

- The noise benefit for coannular nozzles with inverted velocity profiles as measured by P&WA in static model tests was applied to the selected engines having the required nozzle configurations. Section 4.1 describes this coannular noise benefit.

- Fan noise estimates are based on measured noise levels for the P&WA JT3D turbofan. Measured noise levels were averaged to establish the data base for application to the representative AST engines. Corrections were made to the JT3D fan noise data to account for: blade passing frequency, fan diameter, fan loading, rotor-stator axial spacing and the number of fan stages.

- For each engine, a near-sonic inlet was assumed to have a 20 EPNdB reduction in fan noise propagating from the inlet.

- Acoustic treatment was applied to the bypass stream in the duct region behind the fan assemblies. The level of acoustic treatment and the corresponding reduction in fan noise propagating from the duct stream was calculated for each engine. The duct length to height ratio was the geometric parameter correlating the amount of treatment and the noise reduction. Corrections were made for flow Mach number, passage height and treatment backing depth.

The results of these noise estimates are presented in Section 3.2.3.

2.2.5 Emissions

At the same time the Phase II studies were being conducted, P&WA was conducting another NASA contract to evaluate emissions characteristics of experimental combustor configurations for advanced gas turbine engines. This Experimental Clean Combustor Program included an AST Addendum to measure emission characteristics of advanced combustor configurations under simulated cruise conditions. The results of this experimental program were applied to two selected engines at the end of the Phase II study. The results are described in Section 3.2.4.

2.2.6 P&WA Airplane Integration Procedure

Propulsion systems were evaluated using the systems analysis procedure shown schematically in Figure 2.3. This analytical airplane and mission system performs the basic functions of integrating the equations of motion, optimizing cruise altitude, iterating for determining take-off gross weight, etc. The program is modularized and incorporates separate subroutines for calculating aircraft weight and geometry, engine size, aerodynamics, mission profile, and economic characteristics. Among the unique features of this program is the capability of optimizing power settings along the climb path to obtain maximum range. This feature is particularly useful for augmented engines.

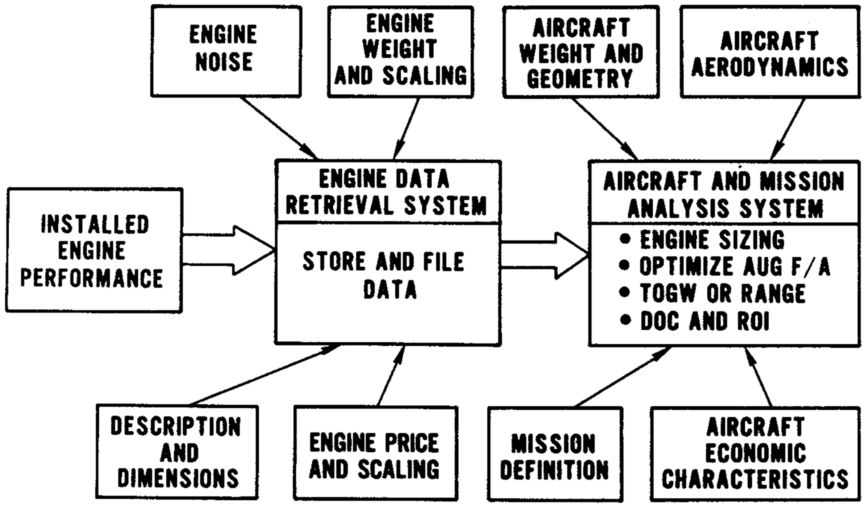


Figure 2-3 *Systems Analysis Procedure*

2.2.6.1 Airplane Characteristics

The baseline airplane used in the P&WA engine evaluation is the NASA Langley Reference Aircraft, as described in NASA CR-132374, Advanced Supersonic Technology Concept Study Reference Characteristics. This is basically a modified arrow wing aircraft carrying 292 passengers with a design range of 4000 NM (7408 km). The NASA Reference Aircraft has a TOGW of 762,000 lbs. (345600 kg), but for purposes of this study, the TOGW was scaled to maintain constant range as propulsion system characteristics changed. An equation defining airframe weight (OEW – Pod weight) as a function of TOGW and wing loading was defined by NASA Lewis for parametric engine evaluation. Aerodynamic polars described in NASA CR-132374 were modified for changes in pod drag from engine to engine, and Reynolds Number changes with flight condition and airplane size. Inlet losses (spillage and/or bypass drag, pressure losses, and boundary layer bleed), engine power extraction, nozzle internal performance and nozzle boattail drag were considered to be thrust losses and charged to engine performance. Nacelle external wave and friction drag were book-kept as airplane drag and charged to airplane performance. The nacelle drag was calculated on the basis of an isolated pod with no interference effects.

2.2.6.2 Key Engine Sizing Parameters

Three key parameters used throughout this study to relate engine and airframe size are:

Parameter*	Related Condition
Airflow Loading (WAT_2/TOGW)	Engine Size
Thrust Loading (Fn/TOGW)	Take-off Field Length
Specific Thrust (Fn/WAT_2)	Jet Noise

*Defined at 200 knots (370 km/hr), sea level operation at standard day +10°C

Engine size, as used in this report, refers to the engine corrected airflow. This corrected airflow is normalized by dividing by the airplane take-off gross weight to determine relative engine airflow size for the airplane. Airflow/TOGW is used as the engine size parameter instead of thrust/TOGW, because most of the engines are not operated at their maximum thrust capability at take-off, due to noise constraints, but are usually operated at their maximum airflow capacity. The range capability of the airplane is essentially a unique function of WAT_2/TOGW parameter for a given engine type. The take-off field length capability is related to the airplane thrust loading, i.e., take-off thrust/TOGW. The higher the thrust loading, the shorter the field length. A value of Fn/TOGW = 0.275 (at STD + 10°C) was estimated to satisfy the 10,500 ft. (3200 m) field length (at STD +15°C) and was therefore used for this study.

Jet noise of an engine is directly related to its specific thrust (thrust/airflow) which is proportional to an average relative jet velocity. By varying the power setting, an engine can operate over a range of specific thrust and noise levels. Each engine has its own characteristic jet noise vs. specific thrust relationship, but for a first approximation, engines tend to have equal levels of jet noise when operated at equal levels of specific thrust.

These three parameters are related by the equation:

$$Fn/WAT_2 = \frac{Fn/TOGW}{4(WAT_2/TOGW)}, \text{ for a 4 engine airplane.}$$

For the given take-off field length capability (Fn/TOGW) and a given relative engine size (WAT_2/TOGW), the operating specific thrust of each engine (Fn/WAT_2) and jet noise were determined. For parametric screening, jet noise was determined using the engine's characteristic noise vs. specific thrust relationship.

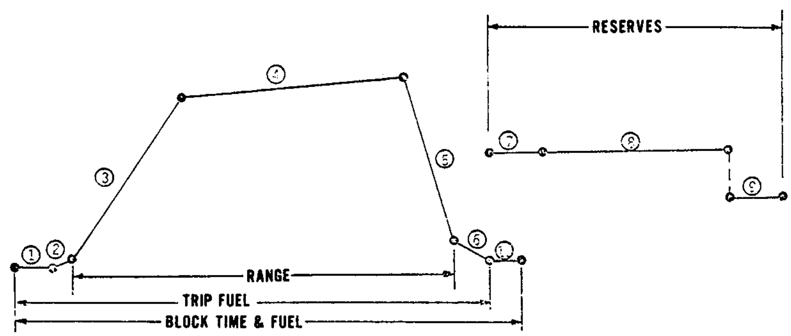
2.3 BOEING STUDY PROCEDURES

Boeing supported the Phase II studies in a subcontractor role by conducting parametric integration studies in Task XIII. The baseline airplane used in these Boeing studies was a delta wing configuration with four podded engines and a maximum taxi gross weight of 750,000 lbs. (340,000 kg). The supersonic range capability was approximately 3500 NM (6500 km) on a hot day using the same fuel reserve rules employed in the National SST Program.

Aircraft range was determined with the following factors held constant:

- Payload – 57,057 lbs. (25,880 kg) (273 passengers)
- Maximum Taxi Gross Weight – 750,000 lbs. (340,000 kg)
- Cruise Mach Number –2.32 (Mn 2.4 on STD day)
- Reference Wing Area – 7700 ft.^{2} (715 m^2)
- OEW Minus Propulsion Pod Weight – 271,920 lbs. (123340 kg)

Engines were sized for maximum range with acceptable sideline noise (FAR 36 traded) and a take-off field length of 12,400 ft. (3780 m) at sea level on a standard +15°C day. Figure 2.4 shows the all supersonic mission profile used to evaluate airplane performance and range sensitivities.



1. TAXI ________ 10 MIN., h_p = 0, GROUND IDLE FUEL FLOW
2. TAKEOFF ________ TO h_p = 35 FT. (10.7 m)
3. ACCEL. & CLIMB TO BCA* ________ TO M = CRUISE
4. SUPERSONIC CRUISE ________ CLIMB CRUISE
5. DESCENT & DECEL ________ FLIGHT IDLE FUEL FLOW
6. ILS APPROACH ________ TO TOUCHDOWN
7. ALLOWANCE ________ 6% TRIP FUEL
8. SUBSONIC CRUISE TO ALTERNATE ________ M = 0.9, h_p = 37800 FT. (11520 m), R= 260 N.MI. (480 km)
9. HOLD ________ 30 MIN., h_p = 15000 FT. (4570 m), M = OPT.
10. TAXI ________ 5 MIN., h_p = 0, GROUND IDLE FUEL FLOW

* BCA = BEST CRUISE ALTITUDE

BASIC SST MISSION PROFILE

Figure 2-4 Basic Mission Profile, All Supersonic

2.3.1 Propulsion Pod Definition

2.3.1.1 Pod Geometry

All the study pods were drawn to a well-established set of rules and constraints. These rules and constraints provided a consistent means of defining the pod external lines for comparative purposes. The pod definition rules are shown schematically in Figure 2.5.

1. The boundary layer diverter height is 11 inches (0.30 m).

2. The intake centerline is parallel to the wing lower surface slope as measured at the intercept of the Mach line at supersonic cruise.

3. The engine centerline is rotated with respect to the intake centerline in order to raise the aft end of the pod as high as possible, without having the pod upper surface interfere with the auxiliary spar.

4. The intercept of the intake and engine centerlines is aft of the rear end of the fully retracted centerbody, and must not exceed an angle of 2.5°. This angle limitation is based on distortion considerations of the airflow entering the engine.

5. The nozzle centerline is rotated with respect to the engine centerline, to direct the exhaust within 0.5° of the wing reference plane. This provides a near optimum supersonic cruise thrust axis.

6. The intercept of the nozzle and engine centerlines is located as far aft as practical, and must not exceed 6°, based again on engine distortion considerations.

7. The minimum cowl depth is 3 inches (0.08 m) over the engine front frame, and one inch (0.03 m) over the engine accessories gearbox.

8. In the side view, the lower surface is a straight line from the tip of the fully expanded nozzle to the clearance point over the front frame or the gearbox, whichever is controlling.

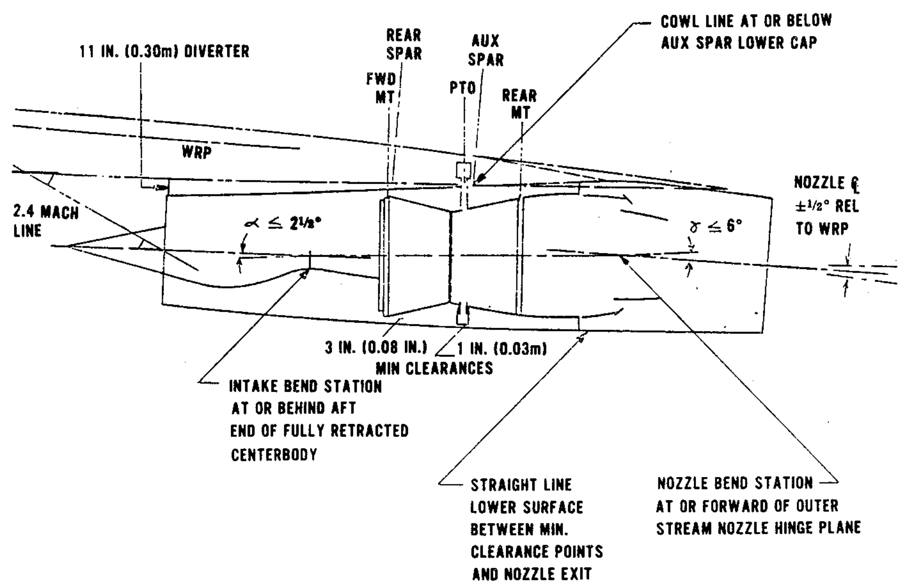


Figure 2-5 *Variable Cycle Engine Pod*

Within these rules and limitations, individual judgments were exercised for each type of engine to complete the geometry definitions. In all cases, the option existed to increase the pod radial dimensions at any station, if it was shown to be beneficial. Exercising this option was conducted separately for each engine.

2.3.1.2 Installation Technique

The baseline airplane has four independent propulsion pods mounted on the underside of the wing near the trailing edge. The inboard pod is located outboard of the main landing gear truck. The landing gear doors are deployed to act as slush/debris deflectors in the gear extended position and thereby reduce the ingestion probability of foreign objects and slush. The separation between inboard engine exhaust jet and horizontal tail was chosen to eliminate the exhause jet impingement on the stabilizer surface during high angle of attack flight maneuvers. The probability of mutual intake unstarts was reduced by providing a lip-to-lip spacing of about 1.8 diameters between inboard and outboard pod and by providing an unstart fence between intake pairs. The airplane stability and control system was designed to handle a mutual intake unstart in conjunction with an engine failure.

The propulsion pods were installed with their maximum diameter sections as near the wing trailing edge as possible to obtain the most favorable interference drag. Aft locations, while favorable to drag, cause other configuration problems such as longer landing gear and compound the airplane aft center of gravity problem and adversely affect the wing flutter characteristics. Figure 2.6 shows why the pod location affects gear weight and the space required for gear stowage. Ground clearance criteria for the engine nozzle hardpoint were observed for all normal aircraft attitudes.

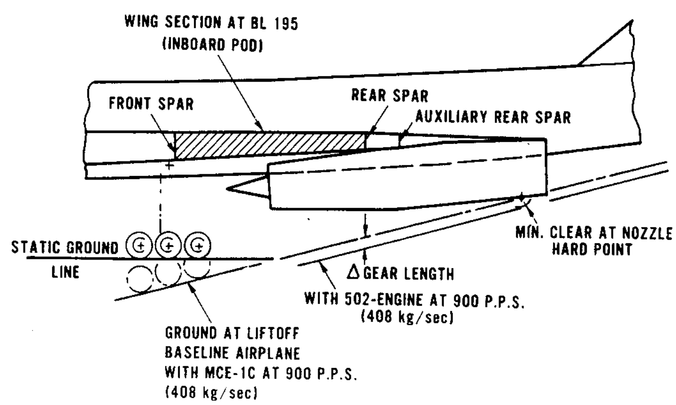


Figure 2-6 *Effect of Engine Installation on Landing Gear Length*

2.3.1.3 Pod Drag

The installed nacelle drag buildup consisted of the following components:

1. Isolated Nacelle Wave Drag – Knowing the installed pod geometry, the installed drag was calculated using established methods. A modified Lighthill theory was used for calculating isolated wave drag. This method gives good agreement with test data for a wide variety of body shapes including bodies with discontinuities in surface shape such as nacelle boattail.

2. Wing-Nacelle Thickness Interference Drag – This drag component is caused by the interference between the nacelles and a thick uncambered wing at zero incidence and calculated using a modification of the supersonic area rule.

3. Wing-Nacelle Lift Interference Drag – The lifting interference was determined using Whitham's theory to calculate the pressure field of each isolated pod. The presence of the thin cambered lifting wing and adjacent nacelles was then accounted for. These effects included the drag of the nacelle pressures acting on the wing camber surface and the drag acting on the nacelle due to the wing lifting pressure. In addition, there was a reduction in drag due to lift because the pod-induced lift enabled the wing to fly at a lower angle of attack. The nacelle shocks and pressure were assumed to reflect away from the wing surface at adjacent nacelles, the so-called "glance" method.

4. Skin Friction Drag – Skin friction drag was calculated using a standard method assuming flat-plate, adiabatic-wall, and turbulent boundary layer.

The complex spillage interference effects were not calculated in this series of parametric studies. Drag calculations were made with the nozzle in the supersonic cruise position. When the nozzle is not in the cruise position, the engine performance data included the boat-tail effects.

The installed nacelle drags were included in the airplane drag polars. Installed nacelle drags were calculated for an engine size of 900 lb/sec (408 kg/sec). Since the variation of drag with engine size is small, the 900 lb/sec (408 kg/sec) drag data were used for all engine sizes.

2.3.2 Engine Performance

Uninstalled engine performance data were converted to installed performance data by making any necessary corrections for differences in intake recovery and/or nozzle gross thrust coefficient (CFG), and by including the effects of the intake excess air drags (bleed, leakage, vortex valve, bypass and spillage).

The pod wave drag, skin friction, and lift/drag interference effects between the wing and pod, that are associated with the basic supersonic cruise pod geometry, were not included in the installed performance. These effects are included in the basic airplane polar definitions. However, drag increments associated with nozzle geometry deviations from the supersonic cruise position are included in the installed engine performance.

2.3.3 Noise Estimation Procedure

Prior studies on the National SST Program have shown that the jet dominated sideline noise is the most difficult of the FAR 36 noise criteria to meet. Sideline noise was therefore selected as the criterion for judging the relative merits of the various types of engines being evaluated.

The static to flight effects for high velocity jet has been a topic of considerable discussion. The effects of forward speed on turbojets have been tested at Boeing in a wind tunnel and with the F-86 airplane. These tests have shown the SAE ARP 876 relative velocity corrections to be applicable to turbojets. Currently, wind tunnel tests are being conducted at

Boeing for dual flow streams. Static model tests of coannular nozzle systems conducted by P&WA indicate significantly lower noise levels than that predicted by SAE ARP 876. Since these noise benefits have not been verified under forward velocity conditions, it was decided to use the SAE relative velocity procedure to estimate the noise levels for the Variable Cycle Engines until forward velocity effects on coannular nozzles have been established.

2.3.4 Airplane Performance Calculation

The method used in this study evaluates airplane performance with a step by step integration of the equations of motion. Inputs to this method include atmospheric conditions, aerodynamic data, weight data, installed engine performance characteristics data and the mission profile. In most cases, it was necessary to adjust the climb power setting schedule to obtain maximum range. Engine size effects on airplane performance were calculated by scaling thrust, fuel flow, and installed engine plus pod weight from the 900 lb/sec (408 kg/sec) reference engine size. Incremental airplane performance was calculated for each leg of the mission.

3.0 RESULTS

3.1 PARAMETRIC STUDY

Performance studies conducted under Tasks VII through XIII of the AST Phase II study were an extension of the Phase I parametric studies. The Phase I studies explored a broad range of conventional and unconventional propulsion systems. The broad scope of the initial study was made possible by applying general ground rules, assumptions and technology projections to each type of engine being evaluated. This general parametric approach allowed numerous concepts to be evaluated effectively with minimum design definition. The Phase II studies consisted of more detailed evaluation of the most promising engine concepts identified in Phase I by applying special and unique refinements to the selected engines.

The types of engines selected for more extensive parametric study were: Duct-Heating Turbofans (which evolved into Variable Stream Control Engines); Low Bypass, Mixed-flow, dry and afterburning Turbojets; and single and dual-valve Variable Cycle Engines. Each engine concept was refined and re-evaluated with special consideration given to: supersonic performance, jet noise, weight, dimensions, and installation characteristics.

3.1.1 Engine Descriptions

3.1.1.1 Low Bypass Engine (LBE)

Previous parametric studies have shown the turbojet engine to be competitive for supersonic cruise aircraft if a highly effective jet noise suppressor system with low pressure loss is assumed. For an all supersonic cruise mission where the relatively poor subsonic cruise performance of turbojets is not a major factor, and if a highly effective jet noise suppressor is applied to the single exhaust stream, the turbojet cycle appears to be an attractive supersonic transport engine. The turbojet studies conducted in Phase I were optimistic in that no allowance was made for cooling either the nozzle or suppressor components.

Parametric evaluation of turbojets in Phase II accounted for this cooling requirement by redefining the turbojet cycle. The resulting mixed-flow Low Bypass Engines (LBE) have bypass ratios from 0.1 to 0.5 in which either some or all of the bypass flow is used for cooling the nozzle/suppressor system. Figure 3.1-1 shows a schematic cross-section of a typical advanced LBE concept. In addition to providing a source of nozzle/suppressor cooling flow, the bypass stream improves TSFC. In fact, supersonic cruise thrust loss with increasing bypass ratio becomes the limiting factor. For those engines where supersonic climb and cruise thrust loss represented an engine sizing criteria, thrust augmentors in the form of afterburners were added to improve climb and cruise thrust capability.

The family of LBE's studied in Phase II were separated into two classes; those engines that utilize a manifold and pipe bypass system (similar to the P&WA J-58 engine), and engines that use an annular duct arrangement similar to that shown in Figure 3.1-1. The class for each cycle was determined by the bypass ratio. For each engine class, component assumptions were assigned commensurate with the bypass system definition.

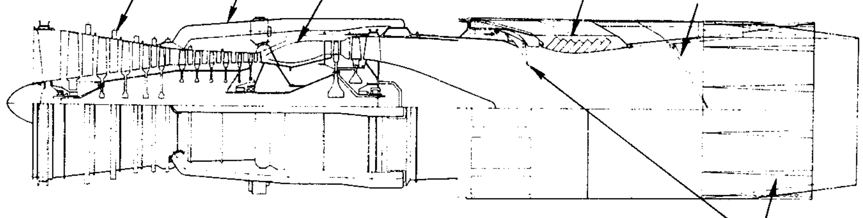


Figure 3.1-1 *Low Bypass Engine*

Several suppressor concepts that are suitable for LBE's have been tested in the SST-DOT program and by various engine and airframe companies. The concept that has the highest effectiveness in terms of noise reduction is the multi-tube design. For the Phase II evaluation of LBE's, advanced multi-tube suppressors were assumed. This multi-tube suppressor configuration is applied to the entire nozzle stream and is stowable for climb and cruise operation. Its noise and performance characteristics are shown in Figure 3.1-7.

3.1.1.2 Variable Stream Control Engines

The Variable Stream Control Engine (VSCE) is an advanced technology refinement of the conventional duct-heating turbofan engine. Advanced technology being evaluated in these and other Phase II parametric engines have resulted in significant improvements in performance relative to the initial definition of the duct-heating turbofan engines evaluated in Phase I. A number of variable geometry and advanced technology components have been included in the Variable Stream Control Engine concept shown in Figure 3.1-2 which evolved from the Phase I turbofans. In addition to the variable geometry components shown in this figure, a low-emissions, low temperature duct-burner, a low emissions primary burner which has a unique throttle scheduling concept, and a coannular nozzle system constitute the basic components of this engine. Some form of variable geometry turbine may benefit the VSCE. However, at this time it is uncertain that the off-design performance improvement associated with variable turbine geometry is sufficient to justify the complexity to the turbine design.

Changes in engine cycle and throttle schedule have significantly improved the supersonic cruise performance and take-off noise characteristics of this engine. Figure 3.1-3 shows the relation of three of the important system variables (supersonic cruise TSFC, engine weight and take-off noise) to changes in bypass ratio and combustor exit temperature. The solid circle represents a conventional turbofan cycle from Phase I. The solid diamond locates a representative VSCE concept. Note the significant improvement in supersonic cruise TSFC while take-off noise remains essentially unchanged. To achieve the same noise level at the lower BPR of the VSCE, the primary burner combustor-exit-temperature is reduced by approximately 600°F (333°C) for take-off. Figure 3.1-3 also shows that the improved performance is offset slightly by an increase in engine weight which results from the decreasing BPR (larger gas generator).

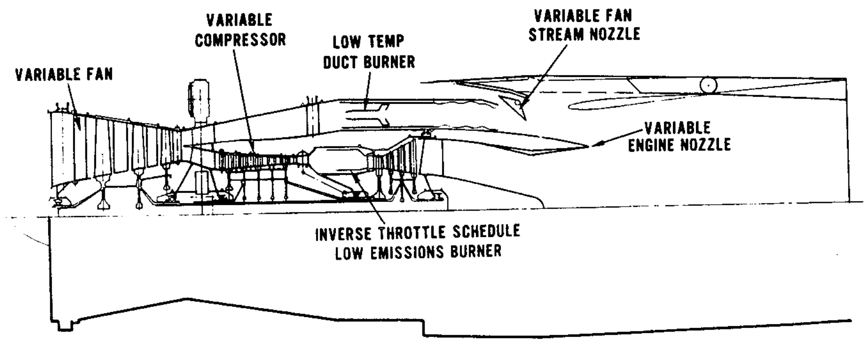


Figure 3.1-2 *Variable Stream Control Engine*

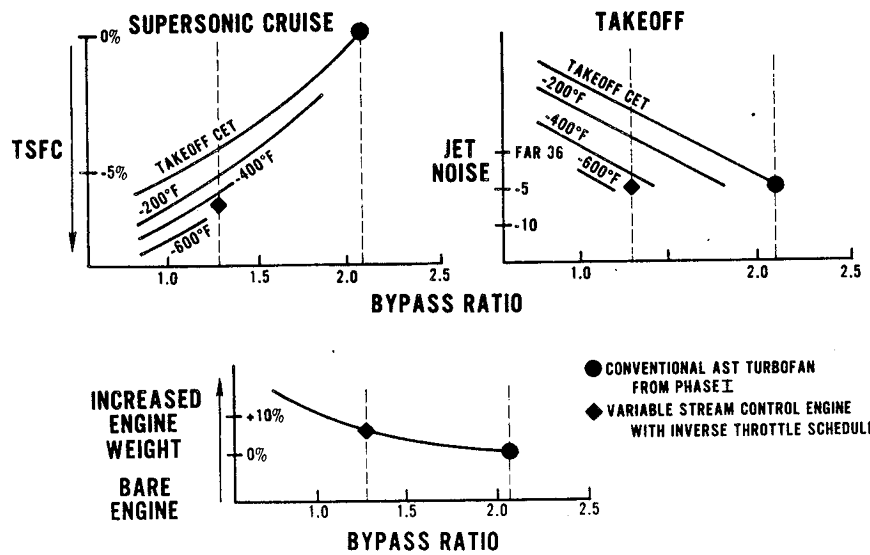


Figure 3.1-3 *Variable Stream Control Engine Cycle Characteristics*

One of the main advantages of the VSCE is its flexibility to take advantage of the noise benefit associated with coannular nozzles or from other types of jet noise suppressors. Figure 3.1-4 shows that if the VSCE is designed without a suppressor, total jet noise can be minimized by properly balancing the primary and bypass stream jet-noise levels. The top curve, which represents the summation of the individual stream noise levels for an unsuppressed engine, shows that the total jet noise is minimum at the point where the fan-duct and primary noise curves intersect. Stream velocities can be adjusted by changing the level of duct-burning and by changing the primary burner power setting. In this manner, thrust can be held constant while stream velocities are balanced to achieve maximum noise benefit from the coannular nozzle or from a suppressor system applied to the bypass stream only. As shown for two representative suppressors, it is possible that total jet noise can be reduced from four to ten EPNdB with no change to the engine cycle or redesign of the engine configuration. This flexibility makes the VSCE concept relatively insensitive to the somewhat uncertain noise reduction characteristics of coannular nozzles and mechanical suppressors in actual flight operation.

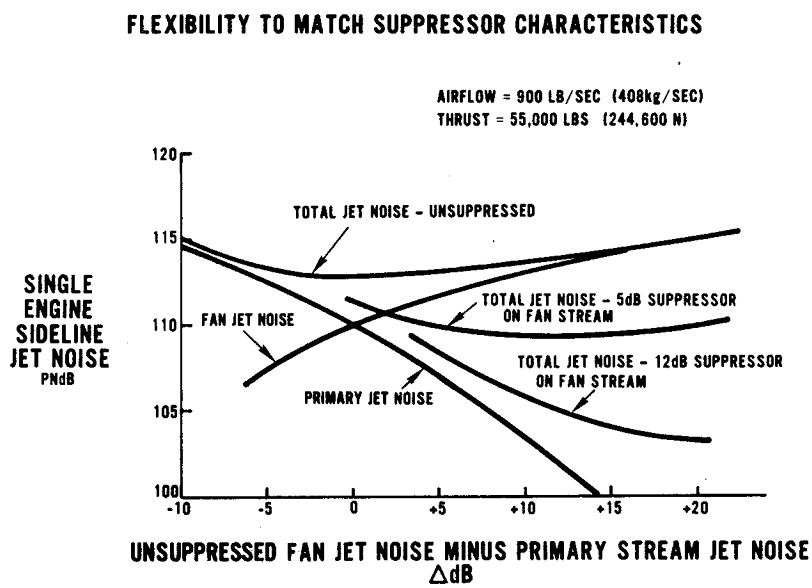


Figure 3.1-4 VSCE Flexibility to Match Suppressor Characteristics

3.1.1.3 Valved Variable-Cycle Engine Concepts

Valved Variable-Cycle Engines (VCE) have the capability for major changes in BPR when going from the design point to some alternate operating condition. Typically, this variation is from a low BPR at supersonic cruise, to a higher BPR condition at take-off and subsonic cruise. For these engines to be suitable for commercial operation, this variation in BPR must be accomplished while maintaining acceptable performance, price, weight and installation features.

Valved VCE concepts studied in Phase II were of two major types; single-forward valve VCE's and dual-valve VCE's. Late in the study, a third concept, the single-rear-valve VCE was evaluated. This rear-valve engine was a derivative of the VSCE and dual-valve VCE concepts and is described in Section 3.2.

Single-Forward-Valve VCE's

One of the simplest methods for accomplishing a variation in BPR is to design a fan that has the capability to accept wide variations in airflow and a corresponding turbine design with a wide variation in work capability. However, fans and turbines operate at reduced efficiencies over the wide range that is required. A more effective method to provide this cycle variation is to design two fan assemblies to operate either in series or parallel. This requires some form of valve to regulate the airflow between the fan assemblies. The two fans can receive their airflow from a common inlet or from separate or auxiliary inlets. The same option applies to the nozzles where either a common variable-geometry nozzle or separate nozzles can be used.

A cross-section of the single-forward-valve VCE concept with series/parallel fans is shown in Figure 3.1-5. During low bypass ratio operation, for supersonic climb or cruise, the two fans operate in series with the air from the first fan flowing directly into the second. For high bypass ratio operation, required for low noise take-off and for subsonic cruise, the air from the first fan is either ducted to a separate nozzle or mixed with air from the second fan. Inlet air to the second fan is obtained by ducting it around the first fan into the second. This parallel mode of operation significantly increases engine bypass ratio and total engine air flow, and reduces the effective fan pressure ratio (and jet velocity) of the cycle.

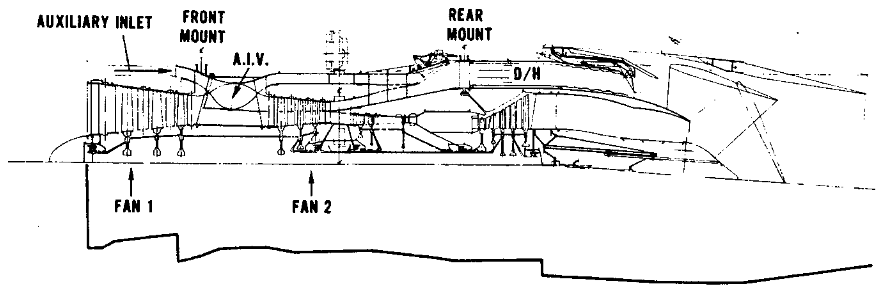


Figure 3.1-5 *Single-Valve Variable Cycle Engine*

In the Phase I studies, several variations of single-forward-valve VCE's were evaluated. From these early parametric studies, it was concluded that the single-forward-valve concept was competitive for low noise levels and therefore should be evaluated further in Phase II. Because of the similarity between these engines and the VSCE concept, many of the features described for VSCE's apply equally to the single-valve VCE.

Dual-Valve Variable-Cycle Engines (VCE's)

The dual-valve VCE concept is similar to the single-valve concept in that it also produces a major change in cycle from take-off to supersonic cruise operation. During take-off and subsonic cruise operation, it operates as a moderate BPR, high overall pressure ratio turbofan engine. During supersonic cruise, it operates as a moderate OPR turbojet. This shift in cycle characteristic is accomplished by adding three major components to the single-valve VCE concept; a rear valve, a second burner system and a second low-pressure turbine assembly (Figure 3.1-6).

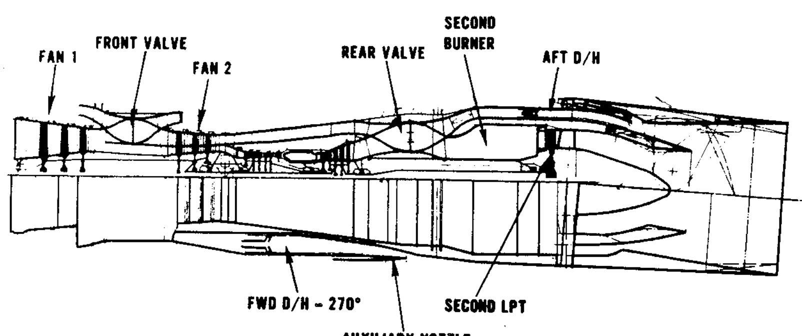


Figure 3.1-6 *Three Nozzle Stream Dual-Valve VCE*

In the high BPR (parallel) mode, like the single-valve VCE, the forward valve ducts first fan exit flow into a bypass stream duct and inlet air into the second fan. The rear valve passes primary and secondary fan flow straight through during high BPR turbofan mode operation. For the three nozzle system which is the configuration shown in Figure 3.1-6, duct-burners are located in both fan streams and can be used during take-off or climb when the engine is in the high BPR mode. The rear duct-burner can also be used for the low BPR mode.

For climb or supersonic cruise, this VCE converts to a turbojet. The first valve is in the straight-through position (first fan flow passes directly into the second fan), and the rear valve is indexed to the inverting position so that gas generator flow is diverted into the outer stream and fan flow is diverted through the second burner and second low-pressure turbine. In this mode, with both burners lit and all flow passing through separate turbines, the cycle is essentially that of a turbojet.

3.1.2 Engine Component Technology

The engine component and material technology utilized for the Phase II studies is based on advanced technology projected for engine certification in the late 1980's or early 1990's. This allows several years for research and evaluation of the critical technology requirements followed by an eight to ten year engine development program. The advanced technology projections are incorporated in all of the conventional and Variable-Cycle Engine definitions evaluated in Phase II.

3.1.2.1 Material Technology

Materials were defined and selected for each engine component with consideration for a proper balance between commercial engine price and weight.

The fan and intermediate case sections are subjected to a maximum inlet temperature of 375°F (191°C) at the Mach number 2.4 condition, and maximum exit temperatures in the 550 to 800°F (288 to 427°C) range, depending on the design fan-pressure-ratio. An advanced high temperature composite material, boron fibers in an aluminum matrix, was selected for the fan blade material in all fan stages except where excessive temperatures precluded its use, in which case, titanium alloys were selected. Titanium alloys were also used in the remainder of the fan and intermediate section, including the vanes, disks, inlet-guide-vane assembly, cases, containment, struts, and seals.

Advanced high-temperature titanium alloys were selected for most of the high pressure compressor elements, including the blades, drum-rotor, hubs, and cases. For fire safety reasons, steel vanes were defined to prevent the possibility of a titanium-on-titanium rub in the event of a rotor-stator axial shift failure. In the higher temperature rear stages of the high-pressure compressor, nickel alloys were substituted for titanium and steel alloys.

The primary materials defined for the burner, including the liner and case, were nickel base alloys. An advanced Oxide Dispersion Strengthened burner liner material was projected to provide flexibility in cooling air distribution for the low emissions burner (section 4.5.3).

For the Phase II study engines, maximum combustor exit temperatures are in the 2600 to 2800°F (1427 to 1538°C) range with maximum turbine cooling air temperatures in the 1150 to 1300°F (621 to 704°C) range. Maximum rotor speeds and stress levels occur at the supersonic cruise condition. Advanced high-temperature materials are required to avoid excessive cooling air requirements which would impose a significant penalty on engine cycle and turbine efficiency. An advanced directionally solidified eutectic alloy material with an advanced coating was selected for the turbine blade material. This material has the potential for increased design stress and temperatures compared to current technology directionally solidified superalloys. Advanced ceramic material, requiring minimal cooling, was selected for the high pressure-turbine inlet guide vanes. The remainder of the turbine vanes and the turbine cases would employ nickel base alloys. The turbine disks require an advanced high creep-strength nickel base alloy (See section 3.4.2).

Titanium or nickel base alloys were selected for the augmentor and nozzle materials, depending on the thermal environment. Honeycomb construction is utilized wherever possible to reduce engine weight. A cost-weight trade study is required to substantiate this choice of construction.

A new and unique engine component required by the valved VCE's is the flow-diverter valve. For the forward valve, which is positioned between two fan assemblies, a high-temperature lightweight composite material (graphite/polyimide) was selected for the walls, with a case constructed of titanium honeycomb. The rear valve is subjected to a much higher temperature environment than the forward valve and was defined with advanced high-strength nickel alloy sheet construction with a honeycomb outer case.

3.1.2.2 Component Technology

A brief description of the advanced technology incorporated in each major engine component is presented in the following paragraphs. Based on these component definitions, engine performance, weight and dimension estimates were made.

Fan

Multi-stage fans were defined with variable camber inlet-guide-vanes and exit-guide-vanes for good subsonic and supersonic cruise efficiency and stability characteristics. The variable camber feature is obtained with variable trailing edge flaps on the inlet-guide-vanes and variable leading-edge-flaps on the exit-guide-vanes. In addition, some of the VCE concepts require variable internal stators for improved inlet/engine airflow matching. The fan efficiency and aerodynamic loading are representative of advanced multi-stage fan designs. A 50 percent axial spacing between each row of airfoils is utilized to reduce fan rotor noise by allowing the wakes from upstream airfoils to weaken by attenuation before striking the next row of airfoils. Further study was undertaken in the Task X preliminary design to increase the axial spacing and the level of acoustic treatment applied to the fan duct. Also, for noise considerations, fan corrected tip speeds were limited to 1600 ft/sec (488 m/sec). All of the fans are constant mean diameter configurations in order to obtain high pressure ratio per stage with minimum cost and weight penalties.

High-Pressure Compressor

High-pressure compressors with pressure ratio from 3.5 to 6.0 were defined to achieve overall cycle pressure ratios in the 15 to 25 range when combined with a multi-stage fan. The compressor inlet-guide-vanes and several rows of variable geometry stators are utilized to obtain good subsonic and supersonic cruise efficiency and stability characteristics. The compressor efficiencies and aerodynamic loadings are representative of advanced axial-flow compressor designs. The compressor corrected tip speeds are approximately 1300 ft/sec (396 m/sec) to achieve high pressure-ratio per stage without incurring efficiency penalties associated with higher tip speeds. Turbine blade and disk stress considerations set the speed of the high-pressure rotor which, combined with the compressor corrected tip speed, establish the compressor diameter. The compressor was also defined as a constant mean diameter configuration to represent an optimum combination of aerodynamic loading, weight, cost and diameter match with the fan and primary burner.

Compressors for Low Bypass Engines

The Low Bypass Engines (LBE) were configured with single-spools for the overall pressure ratios in the 15 to 20 range. Further detailed engine design and performance studies of a one versus two-spool arrangement are required before a final configuration is selected. The low-pressure compressor technology is the same as the fan technology described previously. Slightly higher aerodynamic loading is incorporated in the low-pressure compressor than in the fan definition, due to higher exit Mach numbers made possible by not having a diffuser and duct-burner. However, more variable-geometry stators are required than in the fan definition because of the single-spool configuration. The LBE high-pressure compressor technology is the same as the high-pressure compressor technology, described in the preceding section, except that corrected tip speeds are not as high because of the single spool configuration.

Primary Burner

The primary burner is an advanced burner configuration that minimizes emissions while providing high efficiency and stability. The exact burner configuration will depend on results from the NASA/P&WA Experimental Clean Combustor Program (ECCP), including the AST Addendum (Section 3.1.7), and follow-on burner emissions programs. A specific primary burner definition was selected in the Task X preliminary design to reflect the results to date of the NASA/P&WA Experimental Clean Combustor Program (Section 3.2.4).

Turbines

The single-spool LBE's utilize a two-stage turbine, while the twin-spool VSCE and valved VCE concepts utilize a single-stage high-pressure turbine plus a multi-stage low-pressure turbine. In addition, some of the VCE concepts require a third turbine consisting of a single-stage low-pressure turbine.

Blade stress levels, based on advanced directionally solidified materials, established the maximum allowable rotor speeds. Turbine exit annulus area is set by a maximum exit Mach number of 0.60. Turbine efficiency and aerodynamic loading is representative of advanced turbine designs. Variable-stator geometry was not incorporated in the base parametric definition, but was studied for its potential engine matching improvements.

The total turbine cooling air requirements, including all secondary cooling and leakage airflow, are set as functions of both the maximum combustor exit temperature and the maximum high-pressure compressor exit temperature. In the case of some of the VCE's which utilize an additional rear turbine, fan exit airflow is the source of cooling air for that turbine assembly. The ceramic high-pressure turbine inlet-guide-vanes require a minimal convection cooling scheme while the first-stage blades employ an advanced multi-hole film cooling technique. The remaining stages are either uncooled or employ convection cooling, depending on the local gas temperature.

Duct-Burners

The duct-burners were designed to minimize emissions while maintaining good stability and performance characteristics. A staged ram-induction burner was defined which requires a pilot because of the low temperatures in the bypass stream. This parametric duct-burner definition was redefined as part of the Task X preliminary design to reflect the results of the NASA/P&WA Experimental Clean Compustor Program.

Engine Support and Installation Features

The engine mounts are located at the turbine exit case and the fan inlet case; the forward mount provides the thrust support. In the case of the valved VCE's, the engine mounts are integrated with the flow-inverter valve structure for minimum weight. The high spools, which are relatively low in pressure ratio, have two-bearing support arrangements. The additional rear turbine assembly, required by some of the valved engines, required a fourth low-spool bearing. The single-spool LBE arrangements were defined with three bearings. The engine gearbox and accessories are located externally as a maintenance feature.

Nozzle/Reverser/Suppressor

Two types of nozzle/reverser/suppressor concepts were defined for the parametric engine definitions, a single-stream nozzle with a multi-tube type suppressor for the LBE's and a coannular nozzle configuration for the VCE's.

The nozzle/reverser/suppressor configuration used with the single stream engines is shown in the LBE engine schematic (Figure 3.1-1). Noise suppressor and thrust loss characteristics, shown in Figure 3.1-7, are applied to the entire mixed exhaust stream. The LBE suppressor concept features a multi-tube suppressor that is stowable in the nozzle shroud and operates in conjunction with an ejector system to reduce jet noise. A translating shroud provides ejector air when the tube suppressor is stowed to improve performance for low Mach number operation. Variable throat area provides inlet airflow scheduling capability, and variable exit area allows nozzle operation at optimum area ratio to provide good performance over a range of nozzle pressure ratios. An integrated thrust reverser works in conjunction with the translating shroud for reverse thrust operation.

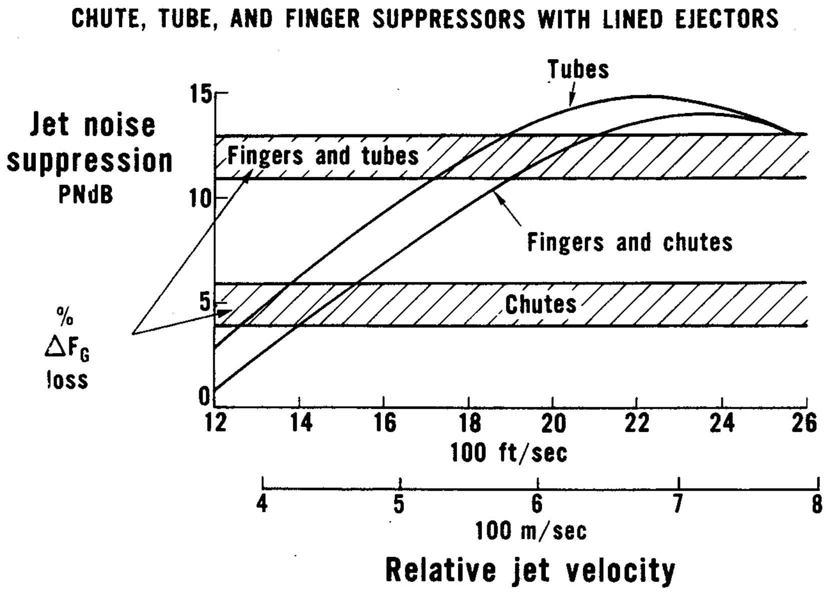


Figure 3.1-7 Jet Noise Suppression Characteristics

The nozzle/reverser definition for the VSCE and valved VCE concepts is shown in Figures 3.1-2 and 3.1-5. Through proper cycle selection and throttle scheduling, the primary stream noise is kept well below that of the bypass stream. Finger, tube or chute mixers operated in conjunction with ejectors were originally defined for jet noise suppression in the outer bypass stream of these engines.

The jet-noise suppression capability that was used for the various suppressor types is shown in Figure 3.1-7. These suppression effects are based on static model test results. The suppression capability actually achievable will depend on results of further testing including flight effects and full-scale effects. The thrust losses for the mechanical mixers are also shown in Figure 3.1-7 and are based on static test results. These nozzle designs were later redefined by eliminating the mechanical mixers to reflect the coannular nozzle jet noise benefit, as results became available from the NASA/P&WA test program (Section 4.1). Variable throat areas in both nozzle streams provide inlet airflow scheduling and fan operating line matching capability, while variable nozzle exit area allows nozzle operation at the optimum area ratio to provide good performance over a range of nozzle pressure ratios. An integrated thrust reverser works in conjunction with the ejector openings during reverse thrust operation. The ejector is also used at low Mach number conditions to improve installed performance.

3.1.2.3 Unique Component Technology

The valved VCE concepts evaluated in this study require a flow-diverter valve, a new and unique engine component. The purpose of this valve is to invert two coannular flows or, in the alternate mode, to allow the flows to pass straight through the valve. This valve is located between two fan assemblies (forward-valve VCE) and/or between the low-pressure turbine and a third turbine assembly (dual and rear-valve VCE's).

Various flow-diverter valve concepts have been devised. The movable-chute concept was defined in Task II of the Phase I studies. Another concept is the Boeing Annulus Inverting Valve (AIV). The AIV offered potential length, sealing and aerodynamic improvements over the movable-chute concept; therefore, the AIV was selected as the baseline definition for the flow-diverter valves used in the Phase II Variable-Cycle Engine parametric studies.

The AIV ducts were sized for a maximum Mach number of 0.5 and a projected 2 percent total pressure loss. The valve length was defined on the basis of an advanced length to flow-height ratio of 4.5. Conceptual design effort on valves conducted under Task VIII is discussed in detail in Section 3.4 of this report.

3.1.3 Parametric Engine Studies

3.1.3.1 Cycle Studies

Selection of engine cycles for refinement studies and data-pack definition for NASA was based on cycle evaluations conducted in Phase II, in addition to the broad parametric studies of Phase I. These studies identified the various cycle parameters (BPR, OPR, FPR and CET) which give the best performance and noise characteristics. Figures 3.1-8 and 3.1-9 are typical of the comparisons used in the cycle studies. The grid in Figure 3.1-8 shows the effect of BPR and OPR on non-augmented supersonic cruise performance. As shown, relatively large improvements in performance are possible with the proper selection of cycle parameters. Figure 3.1-9 shows that for a given take-off airflow size, the thrust required for supersonic cruise and the corresponding augmentation level has significant impact on TSFC, depending on the engine cycle. These higher augmentation levels result in poorer TSFC. Trends of the type illustrated in these two figures were used to screen and select the best representative cycles for each engine concept.

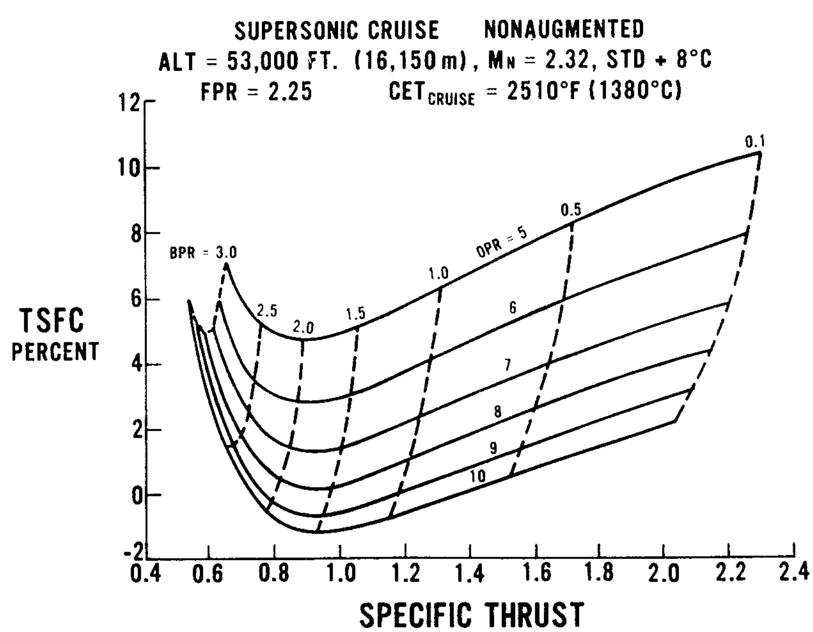


Figure 3.1-8 *Variable Stream Control Engine Parametric Trends - Non Augmented Supersonic Cruise*

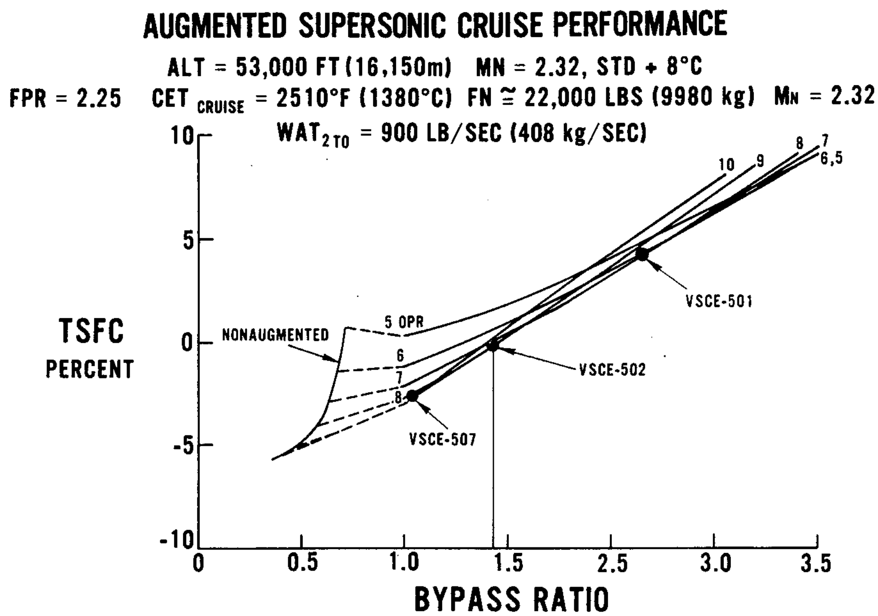


Figure 3.1-9 *Variable Stream Control Engine Parametric Trends - Augmented Supersonic Cruise*

3.1.3.2 Variable Stream Control Engine (VSCE)

The VSCE concept is described in Section 3.1.1.2. Based on conclusions drawn from previous parametric studies and from the cycle studies, a parametric study was conducted to determine the overall system and noise sensitivity to reductions in cycle BPR and fan pressure ratio (FPR). For each of the cycles evaluated, the take-off combustor temperature levels were set such that the maximum benefit could be derived from either a jet-noise suppressor in the bypass stream, or the coannular noise benefit. At the same time, the maximum combustor exit temperature at the supersonic cruise condition was set at 2600°F (1427°C). Thus, each cycle was defined with a different level of Inverse Throttle Schedule (ITS) depending on its FPR and BPR.

Table 3.1-I contains a summary of the take-off (sea level static) cycle characteristics of each engine evaluated. As shown, a single overall pressure ratio (OPR) was selected. This OPR was selected based on past studies considering a potential cruise mission Mach number requirement of 2.7 and a maximum compressor discharge temperature limit of 1300°F (704°C).

Figures 3.1-10, -11 and -12 compare the installed subsonic and supersonic cruise performance of the seven parametric engines summarized in Table 3.1-I. The installed performance data includes such effects as: inlet losses associated with the baseline Mach number 2.4 axisymmetric inlet, representative levels of engine bleed and horsepower extraction, and both internal nozzle performance and external boattail losses. Shown on each of the figures are P&WA estimates of typical operating power settings for each of the engines. These estimates were based on preliminary system evaluations of each engine in the NASA reference airplane.

TABLE 3.1-I

VARIABLE STREAM CONTROL ENGINE SUMMARY

SEA LEVEL STATIC TAKEOFF POINT		VSCE 501	502	507	503	504	505	506
FAN PRESSURE RATIO		3.3 →			2.5 →		4.1 →	
OVERALL PRESSURE RATIO		15:1 →						
BYPASS RATIO		2.1	1.3	1.0	1.9	1.5	1.0	0.5
COMBUSTOR EXIT TEMP								
TAKE-OFF °F	STD + 18°F	2700	2300	2150	2250	2100	2350	2000
°C	STD + 10°C	(1480)	(1260)	(1180)	(1230)	(1180)	(1290)	(1090)
SUPERSONIC CLIMB °F	STD+14.4°F	2600 →						
°C	STD + 8°C	(1430) →						
TOTAL FAN CORRECTED AIRFLOW								
	lb/sec	900 →						
	kg/sec	(408) →						

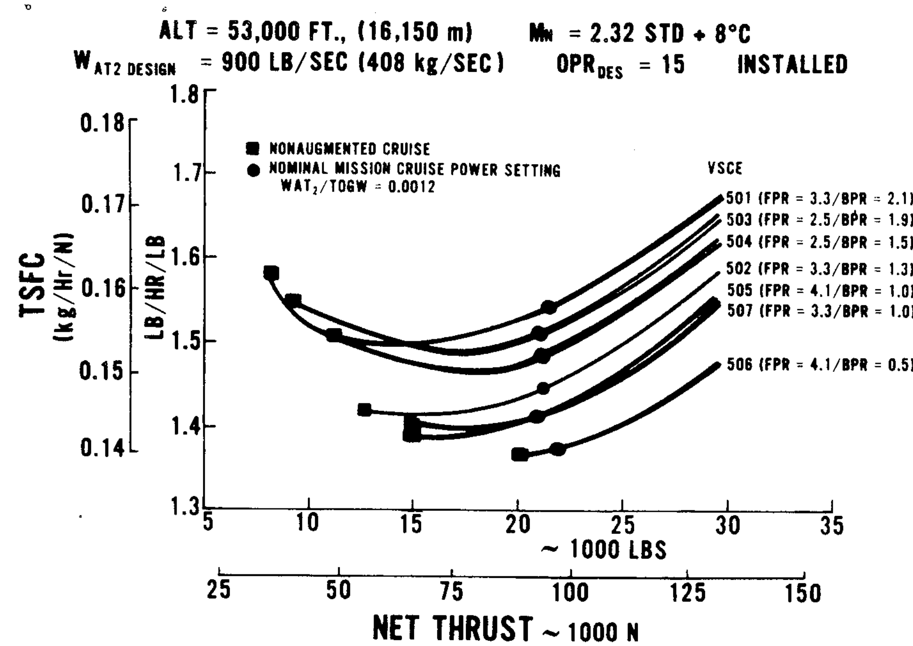


Figure 3.1-10 Estimated Supersonic Cruise Performance for VSCE Cycles

A comparison of the augmented supersonic cruise performance (Figure 3.1-10) shows that in all cases, reducing BPR results in better TSFC. This figure also shows that for engines with the same BPR but differing FPR's (VSCE's -505 and 507), there is little change in cruise performance.

Although improvements in supersonic cruise performance can be achieved through reductions in BPR, the installed subsonic cruise performance data (Figures 3.1-11 and -12) show that there may be a loss in subsonic performance. This loss is indicated by the typical nominal mission cruise power settings shown on the figures. In addition to the loss in subsonic performance, Figure 3.1-13 shows the trend of increasing engine weight with decreasing BPR.

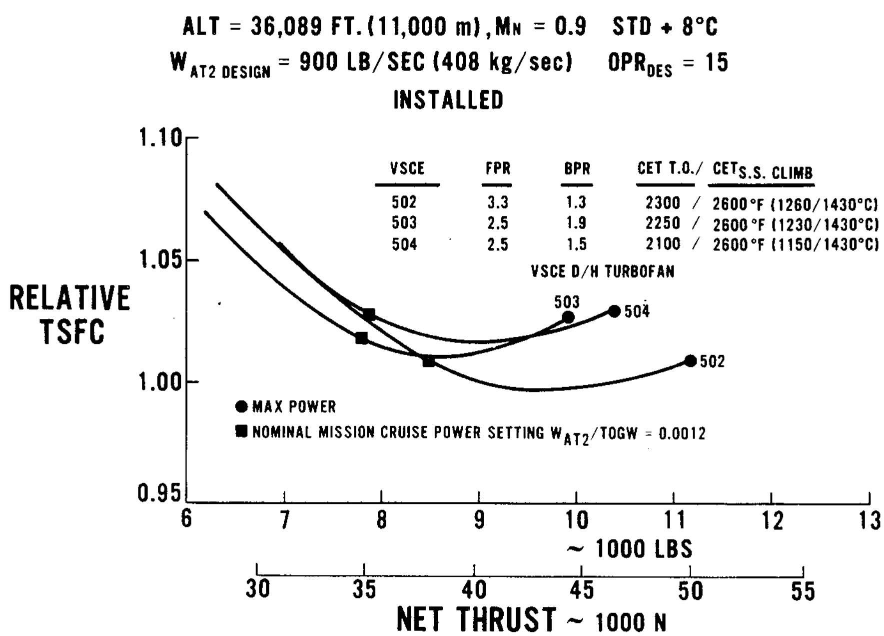


Figure 3.1-11 Estimated Subsonic Cruise Performance for VSCE Cycles

To sort out these opposing effects, the family of VSCE's was evaluated on an overall system basis to help select the best cycle combination. For this evaluation, a chute-type jet-noise suppressor was applied to the engine bypass streams. The engines were sized to provide a lift-off thrust loading of 0.275 with a power setting corresponding to a bypass stream relative jet velocity of 2250 ft/sec (690 m/sec). This power setting was selected because it corresponds to a point of near maximum suppressor effectiveness (Figure 3.1-7). The results shown in Figure 3.1-14 indicate that the best BPR is in the 1.0 to 1.3 range with a FPR from 3.3 to 4.1. The increased engine weight (Figure 3.1-13) and poorer subsonic performance of the lower BPR VSCE-506 engine offsets its improved supersonic cruise TSFC.

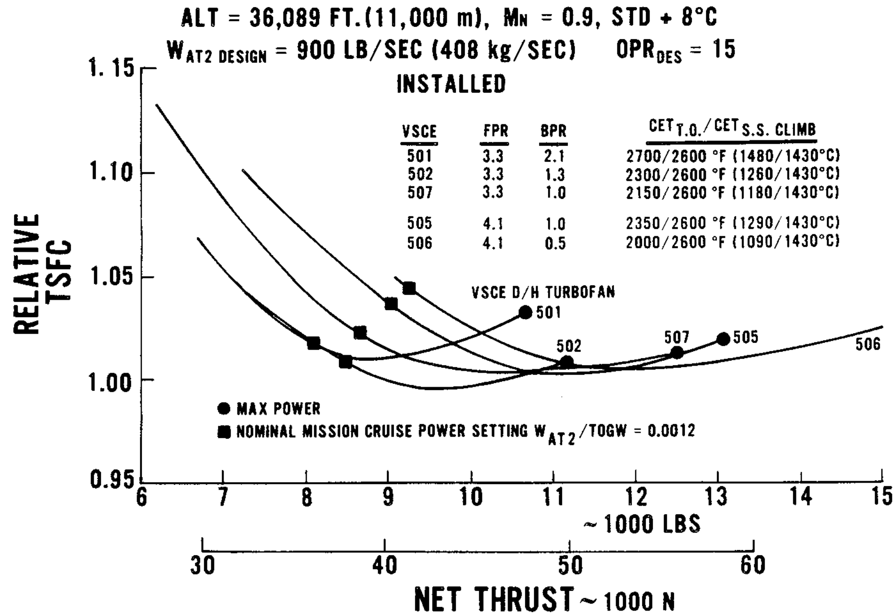


Figure 3.1-12 Estimated Subsonic Cruise Performance for VSCE Cycles

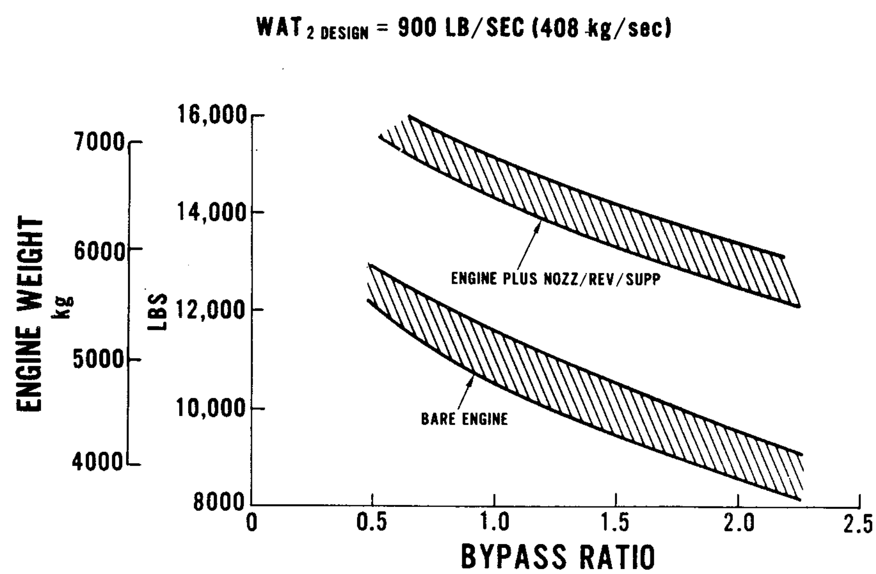


Figure 3.1-13 VSCE Weight Trend

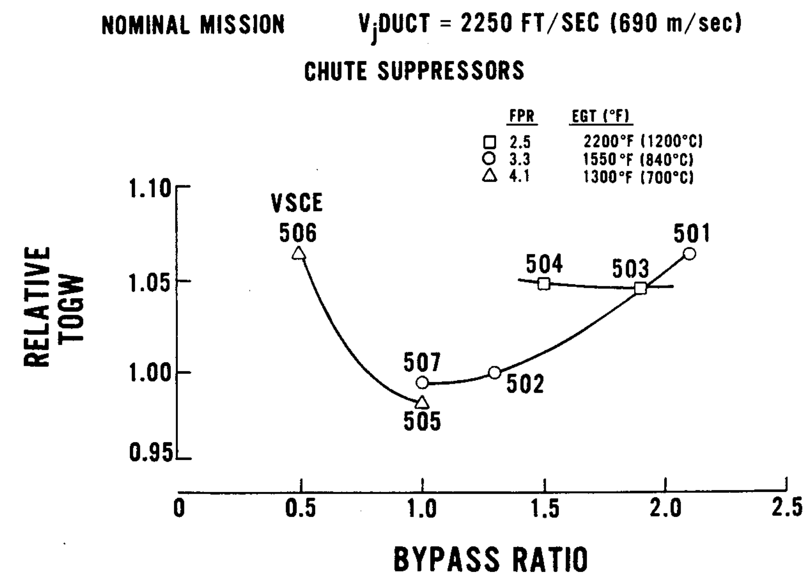


Figure 3.1-14 VSCE Cycle Optimization

In terms of TOGW vs. noise, the results for the VSCE's are shown in Figure 3.1-15. The solid lines represent the results for engines incorporating chute suppressors in the bypass streams only. The triangular point on each curve represents a minimum engine size being operated at a high take-off power setting with a resultant high bypass stream jet-velocity level of 2500 ft/sec (760 m/sec). Moving along each line toward lower noise levels corresponds to increased engine size and lower take-off power settings. The engine size corresponding to a lower power setting yielding 2250 ft/sec (690 m/sec) fan-jet velocity in the bypass stream is shown by the circular point. Engines sized by this criterion are near the "knee" of each curve. Because of the assumed suppressor characteristics (Figure 3.1-7), increasing engine size beyond this point does not result in significant reductions in jet-noise.

Shown for comparison with the chute suppressed VSCE's is the TOGW vs. noise relationship for an unsuppressed VSCE-502 based on the SAE noise prediction procedure. In addition, results for the unsuppressed VSCE-502 based on the coannular model static test data are shown and indicate the potential noise and TOGW benefit of the coannular nozzle.

Figures 3.1-14 and -15 indicate that the best FPR is 3.3 to 4.1; however, at this time it is difficult to narrow the FPR selection further because of the preliminary nature of the coannular noise benefit estimates and because specific noise requirements have not been established for advanced supersonic transports. The VSCE-502 engine was selected as the best representative VSCE cycle. It was also selected for further VSCE refinement studies and for release in data-pack form.

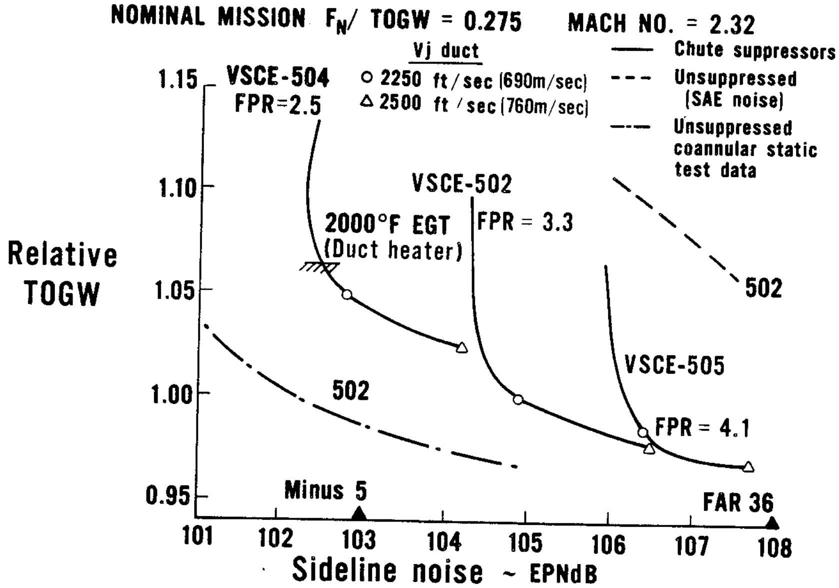


Figure 3.1-15   Noise Comparison of VSCE's

3.1.3.3 Low Bypass Ratio Engines (LBE)

The previous parametric studies conducted in Phase I indicated that the turbojet engine could be competitive for a commercial supersonic transport aircraft if a low pressure loss, highly effective jet-noise suppressor system is assumed. As described in Section 3.1.1, these broad parametric studies were optimistic in that no allowance was made for cooling the nozzle/reverser/suppressor system. To account for this requirement and to take advantage of the decrease in engine weight with increasing bypass ratio, turbojet concepts evaluated in Phase II were low bypass ratio, mixed-flow engines in which either some or all of the bypassed flow was used for cooling the nozzle/suppressor system. Table 3.1-II shows the matrix of Low Bypass Engine (LBE) cycles that were evaluated to determine the most attractive LBE cycle for more detailed system evaluation.

As a result of this parametric study, an overall pressure ratio (OPR) of 17:1 was selected based on engine performance trends and on the 1300°F (700°C) compressor exit temperature limit corresponding to a 2.7 Mn cruise condition. The BPR range selected for study was from 0.1 to 0.5. In addition, as a result of the parametric study which showed matching benefits with Inverse Throttle Schedules (ITS), the take-off to cruise throttle ratio was altered in each of the engines selected for more detailed system evaluation. Table 3.1-III shows the four LBE cycles selected for detailed performance and system evaluation.

Figures 3.1-16 and -17 show supersonic and subsonic cruise part power performance for each of the engines shown in Table 3.1-III. The installed performance shown includes corrections for inlet drag, representative levels of engine bleed and horsepower extraction, internal nozzle performance, and external nozzle boattail drag. For the part power conditions shown, inlet drag is minimized by throttling the engine while holding engine airflow constant over a range of power settings. Engine airflow is held constant by varying the nozzle throat area.

TABLE 3.1-II

LOW BYPASS ENGINE CYCLE MATRIX

CORRECTED AIRFLOW ($W_{AT2\ DESIGN}$)	900 lb/sec (408 kg/sec)
BYPASS PRESSURE RATIO	3.3 - 5.0
BYPASS RATIO	0.1 - 0.5
OVERALL PRESSURE RATIO	12 - 25
COMBUSTOR EXIT TEMPERATURE	
HOT DAY TAKEOFF	2200 - 2700 °F (1200 - 1480 °C)
HOT DAY MAX CLIMB	2600 °F (1430 °C)

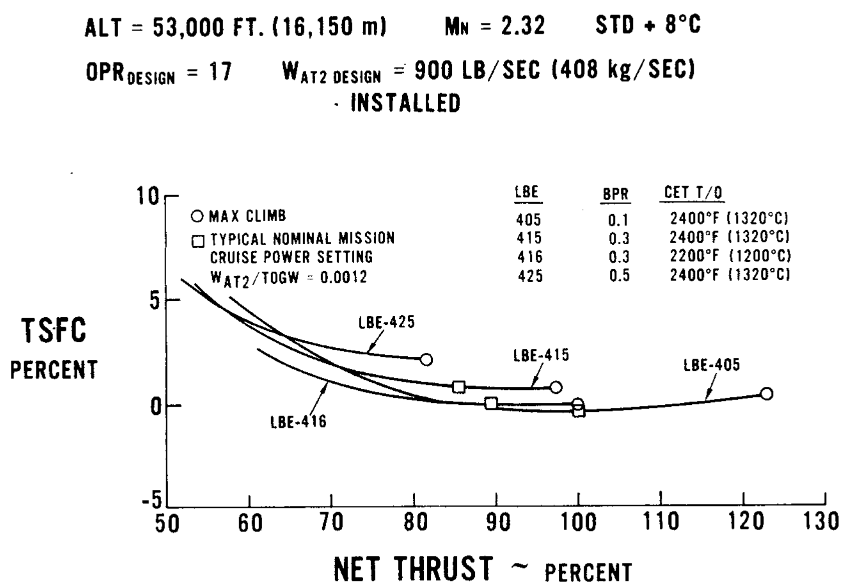


Figure 3.1-16 Estimated Supersonic Cruise Performance for LBE Cycles

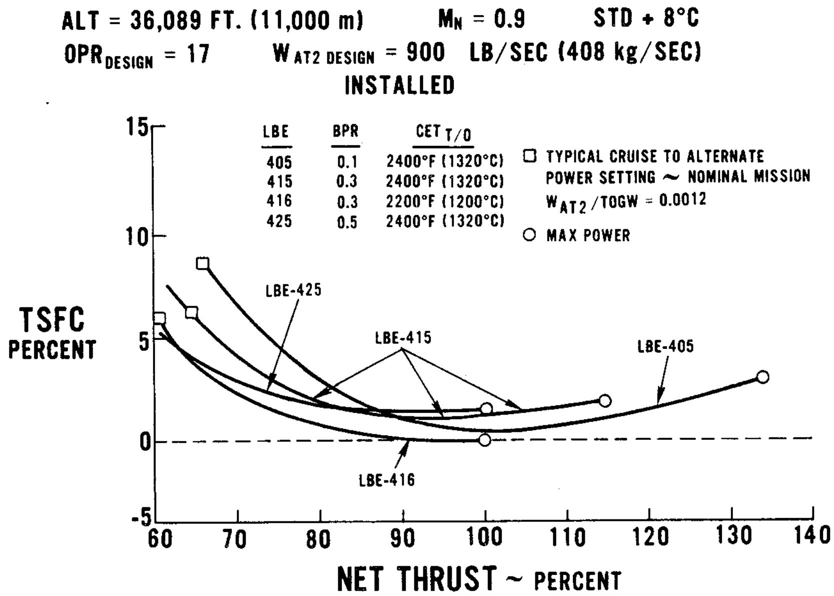


Figure 3.1-17 Estimated Subsonic Cruise Performance for LBE Cycles

TABLE 3.1-III

SELECTED LOW BYPASS ENGINE CYCLES

		LBE			
SEA LEVEL STATIC TAKEOFF POINT		405	415	416	425
BYPASS PRESSURE RATIO		4.3	3.7	3.3	3.4
OVERALL PRESSURE RATIO		17	→	→	→
BYPASS RATIO		0.1	0.3	0.3	0.5
COMBUSTOR EXIT TEMP					
T.O. STD + 18°F	°F	2400	2400	2200	2400
STD + 10°C	°C	(1320)	(1320)	(1200)	(1320)
SUPERSONIC CLIMB					
STD + 14.4°F	°F	2600	→	→	→
STD + 8°C	°C	(1430)	→	→	→
TOTAL FAN CORRECTED AIRFLOW					
LB/SEC		900	→	→	→
Kg/SEC		(408)	→	→	→
AUGMENTATION		YES	YES	YES	YES

Figures 3.1-18 and -19 show how the various LBE's compare in terms of airplane TOGW and engine size. Since both the 0.3 and 0.5 BPR engines studied were marginal in transonic climb thrust margin, afterburning versions of both cycles were evaluated (LBE-416 aug and LBE-425 aug). These engines had improved thrust margins, but because both engine weight and TSFC increased, no improvement in airplane TOGW resulted (Figure 3.1-18). Figure 3.1-19 shows that for engines sized in the 0.0011 airflow/TOGW size, which would be equivalent to FAR 36 (suppressed), the 0.1 BPR turbojet cycle achieves the lowest TOGW of any of the LBE's studied. On the basis of these systems studies, the 0.1 BPR LBE-405 engine was selected as the best engine of this type and was prepared for data-pack release.

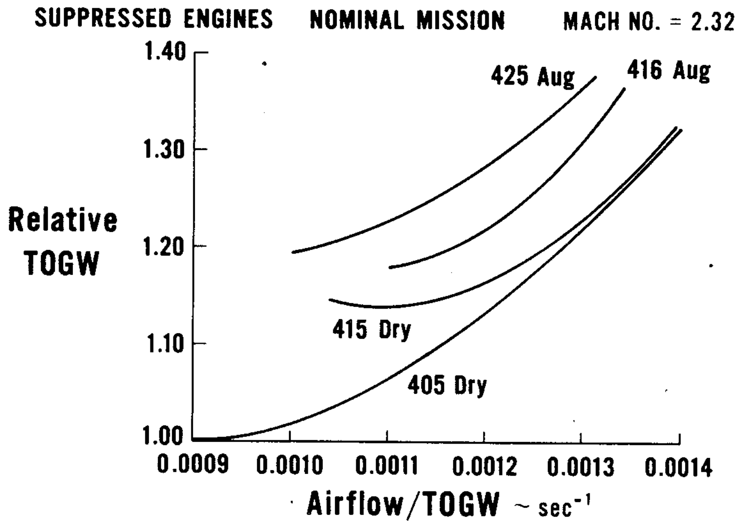


Figure 3.1-18 System Comparison of Low Bypass Engines

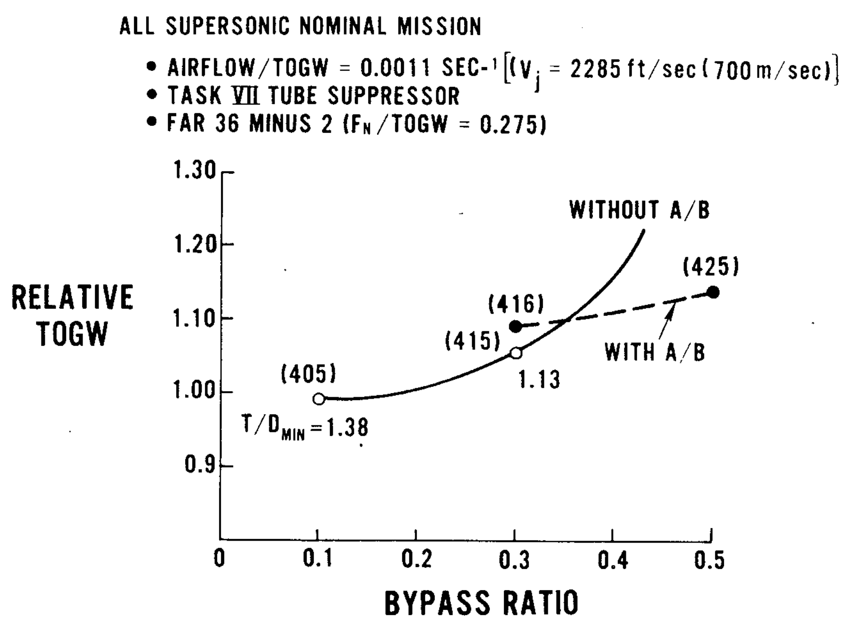


Figure 3.1-19 LBE Cycle Optimization

3.1.3.4 Single-Front-Valve Variable-Cycle Engines

The studies that were conducted on the single-front-valve Variable-Cycle Engine (VCE) were formulated to compliment the broad parametric studies of the Phase I studies. Although still parametric in nature, these studies were designed to explore improvements and refinements relative to the early definitions of front-valve VCE concepts.

Because of the similarity between these front-valve cycles and the VSCE's, many of the trends established for VSCE's apply also to these single-valve engines. For example, conclusions drawn with regard to the best OPR level for the VSCE's apply also to the front-valve VCE's. Therefore, the front-valve engine parametric studies concentrated on the impact of more unique cycle characteristics such as the sensitivity of FPR, BPR, ITS, and airflow schedule on supersonic and subsonic performance.

Two arrangements were evaluated: mixed fan-duct flow vs. separate flow. The front-valve engine shown in Figure 3.1-20 has a mixed fan-duct flow leading to a single duct-burner. An alternate design (similar to the VBEIA concept from Phase I) has separate fan streams so that when the engine is operating in the high BPR mode, the bypass streams from the two fans do not mix. This alternate arrangement allows more flexibility in the basic cycle in that the two duct-streams, because they are not mixed, do not require static pressure balancing and more importantly do not experience the large shifts in duct corrected flow (Mach number) or pressure loss with changes in mode (high to low BPR). Another benefit is that the outer stream may be used to bypass excess inlet air when the engine operates in the low BPR mode. A disadvantage is that two duct-heaters would be required to balance the stream noise levels during augmented take-off. For the purpose of allowing maximum flexibility during the initial screening of the parametric single-valve engines, only separate fan-stream configurations were evaluated. Later refinement studies centered on the mixed-flow configurations since they offered potential weight improvements.

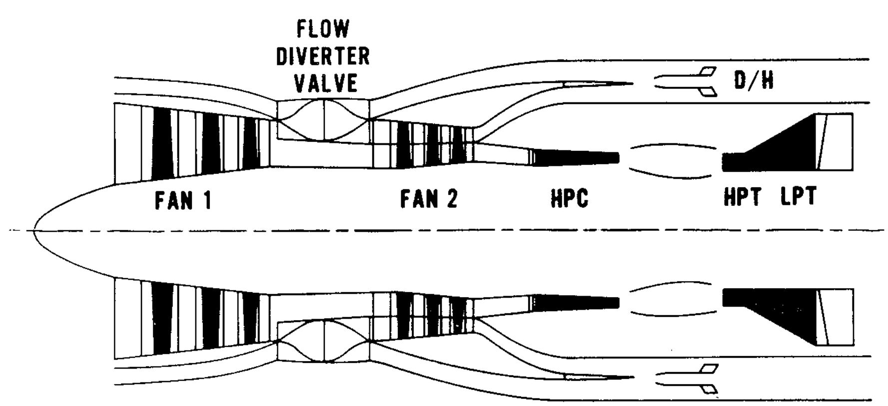


Figure 3.1-20 Single Valve Variable Cycle Engine, Mixed Fan-Duct Flow Configuration

As with the VSCE concepts, a preliminary evaluation of the Inverse Throttle Schedule (ITS) technique resulted in a significant improvement in single-front-valve VCE performance. Table 3.1-IV compares the take-off cycle characteristics of a baseline front-valve VCE (VCE-102) with an ITS cycle in which both the take-off CET and BPR have been significantly reduced. As shown in Table 3.1-IV and Figure 3.1-21, a direct result of ITS is a significant increase in supersonic cruise airflow (from 42 to 66 percent of take-off airflow) without an increase in the primary nozzle jet area requirement. Figure 3.1-21 also shows that for constant FPR, reducing the engine BPR in combination with ITS increases supersonic cruise thrust and reduces TSFC. For the ITS engines, the increase in thrust is partly due to the reduction in BPR and partly due to the increase in supersonic cruise airflow. The net result of these changes is that the amount of duct-burner augmentation required to meet supersonic cruise thrust requirements is reduced. In addition, increasing the supersonic cruise engine airflow makes the engine more compatible with the representative inlet system. It is expected that fully installed, the difference in TSFC between the ITS single-valve VCE and the base VCE should be even greater than the uninstalled improvement shown in Figure 3.1-21 due to the elimination of inlet bypass flow at supersonic cruise conditions.

TABLE 3.1-IV

SINGLE FRONT-VALVE VCE PARALLEL MODE CYCLE PARAMETERS

	VCE-102	ITS* VCE-107
CORRECTED AIRFLOW		
WAT_2 ~ LBS/SEC	900	→
(WAT_2 ~ KG/SEC)	(408)	→
BYPASS RATIO	3.3	1.5
FAN PRESSURE RATIO - 1	2.5	→
FAN PRESSURE RATIO - 2	2.5	→
CYCLE PRESSURE RATIO	15:1	→
COMBUSTOR EXIT TEMP (°F)		
HOT DAY TAKEOFF	BASE	-760
HOT DAY MAX CLIMB	BASE	→
WAT_2 CRUISE/WAT_2 TAKEOFF (%)	> 42	> 66

* INVERSE THROTTLE SCHEDULE

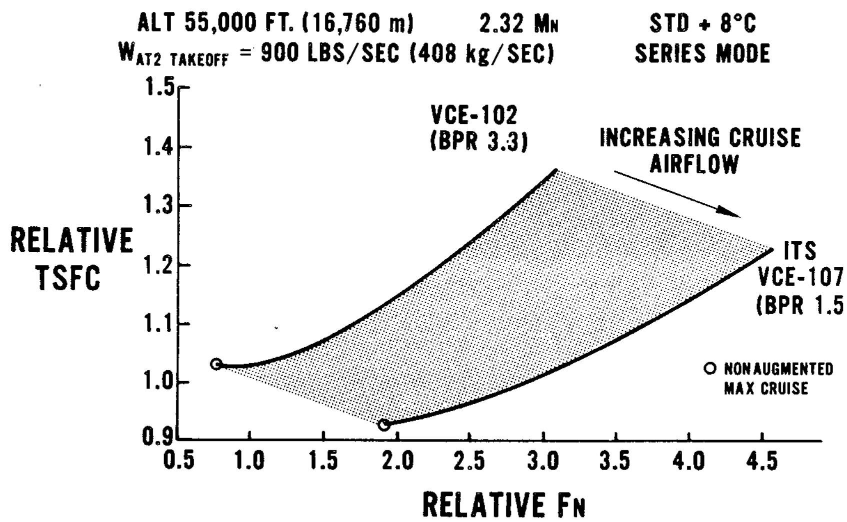


Figure 3.1-21 *Single Front Valve VCE Estimated Supersonic Cruise Performance*

Figure 3.1-22 shows that at subsonic cruise, despite the VCE-107's lower BPR (1.5), it has a level of TSFC and thrust that is comparable to the higher BPR VCE-102 engine. Therefore, the VCE-107's improvement in supersonic cruise performance is not accompanied by a compromise in subsonic performance.

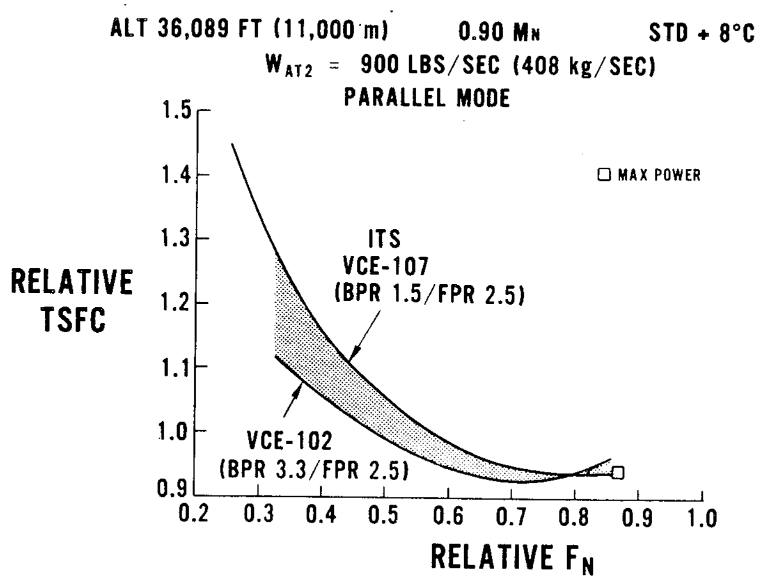


Figure 3.1-22 *Single Front Valve VCE Estimated Subsonic Cruise Performance*

In order to select an engine for data-pack release, each of the parametric single-valve VCE's was evaluated on an overall system basis. Since each of the engines evaluated had similar noise characteristics, engines were compared at the same airflow to TOGW ratio, which corresponds to a constant level of sideline jet noise. For a constant airflow/TOGW of 0.0013, Figure 3.1-23 shows that the VCE-107, with 1.5 BPR, has the lowest TOGW of the three separate stream front-valve VCE's evaluated. However, the VCE-107M, a two stream version which provides for mixing of the two fan-streams in the high BPR mode, gave slightly lower TOGW than the three stream version and was estimated to have better installation characteristics. As a result, the VCE-107M engine was selected for data-pack release.

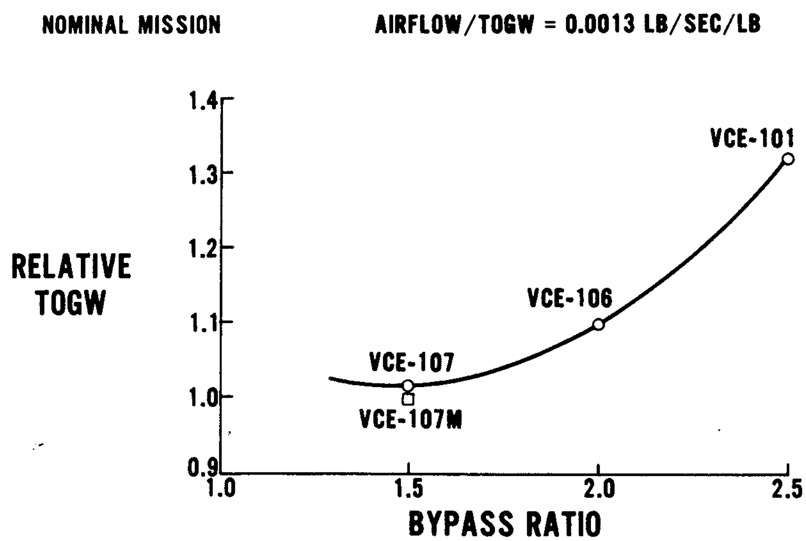


Figure 3.1-23 Single Front Valve VCE Bypass Ratio Selection

3.1.3.5 Dual-Valve Variable-Cycle Engines

Because of the complexity and the uniqueness of the dual-valve Variable Cycle Engine (VCE) concepts relative to the other engine types, it was necessary to increase both the range and number of cycle parameters to be evaluated in this study. Table 3.1-V shows the broader range of overall pressure ratio (OPR) and BPR which were chosen for study with a new variable, turbine work split, included in the list.

For each combination of fan pressure ratio (FPR), BPR, OPR, and combustor exit temperature (CET), a minimum of four different values of low-pressure turbine work split were evaluated. This parameter is significant since it determines the fan match and fan surge margin when the engine is operated in the twin turbojet mode. Turbine work split is defined as the ratio of work in the first low-pressure turbine (LPT) assembly (located upstream of the rear valve) to total turbine work in both LPT assemblies.

TABLE 3.1-V

RANGE OF DUAL VALVE VCE CYCLE PARAMETERS

RANGE OF VARIABLES ~ (PARALLEL MODE)	
• BYPASS RATIO	2.0 - 3.5
• FAN PRESSURE RATIO	2.0 - 3.5
• CYCLE PRESSURE RATIO	15 - 25
• LOW TURBINE WORK SPLIT (%)	40 - 90
• TAKEOFF PRIMARY COMBUSTOR TEMP	2600 - 2800°F (1430 - 1540°C)
• SECONDARY COMBUSTOR OUTLET TEMP	UP TO 2500°F (UP TO 1370°C)
• AUGMENTER TEMP	UP TO 2500°F (UP TO 1370°C)
• CRUISE FLIGHT M_N	2.2, 2.4, 2.7
• NOISE GOALS	FAR PART 36 TO FAR 36-10

Table 3.1-VI lists the three-stream dual-valve VCE's studied. With the exception of the VCE-201B & C cycles, all engines were matched to the same inlet airflow schedule at supersonic cruise. The VCE-201A, B and C cycles had the same cycle characteristics at take-off but were evaluated with different supersonic cruise airflow levels.

TABLE 3.1-VI

DUAL VALVE VCE CYCLES EVALUATED

PARALLEL MODE

CYCLE NO	BPR	FPR/FPR_2	OPR	CET (°F)	CET (°C)	TURBINE WORK SPLIT	CRUISE INLET AIRFLOW SCHEDULE
201A	3.0	2.5/2.5	20:1	2600	1430	70/30 - 40/60	BASE
201B	3.0	2.5/2.5				70/30	+15%
201C	3.0	2.5/2.5				70/30	+23%
202	3.0	2.5/3.0				70/30 - 40/60	BASE
207	3.5	2.5/2.5					
209	2.5	2.5/2.5					
210	2.5	2.5/3.0					
211	2.5	3.0/3.0					
212	2.0	3.0/3.0					
213	2.0	3.0/3.5					
214	2.0	2.5/2.5					
215	3.0	2.5/2.5	25:1				
216	3.0	2.5/2.5	20:1	2800	1540		
217	3.0	2.5/2.5	15:1	2600	1430		

Table 3.1-VII is a summary of the most attractive dual-valve VCE's matched to the same cruise airflow schedule. It indicates that although the engines evaluated were quite different in cycle characteristics, the difference in engine performance was small. The cycle with the best supersonic cruise performance and largest subsonic cruise thrust margin was the 2.0 BPR VCE-213 cycle. However, these performance improvements relative to the base 3.0 BPR cycle were achieved at the expense of increased engine weight.

For the nominal (all supersonic) and mixed mission, a system evaluation of three engines that cover a range of bypass ratios from 2.0 to 3.0 is shown in Figure 3.1-24. The 3.0 BPR VCE-201A cycle shows a slight advantage relative to the other dual-valve cycles. These results indicate that the weight increase for the lower bypass ratios offsets the supersonic performance advantage these lower BPR cycles have. When sized for low airflow/TOGW levels (higher noise levels), the 3.0 BPR engine is marginal in subsonic cruise thrust. This requires augmentation for the mixed mission which would eliminate the small advantage that this engine has relative to the other lower BPR engines.

TABLE 3.1-VII

THREE-STREAM DUAL VALVE PERFORMANCE COMPARISON

		DESIGN PARAMETERS SEA LEVEL STATIC STD. DAY				RELATIVE* TAKEOFF NOISE	RELATIVE SUBSONIC CRUISE PERFORMANCE	RELATIVE SUPERSONIC CRUISE TSFC
VCE NO.	BPR	FPR^1/FPR^2	OPR	CET (°F)	CET (°C)	~ΔPNdB	FN/TSFC (%)	(%)
201A	3.0	2.5/2.5	20:1	2600	1430	BASE	BASE/BASE	BASE
202	3.0	2.5/3.0				+2	0.0/0.0	-0.9
211	2.5	3.0/3.0				+2	+15/-0.5	-1.8
213	2.0	3.0/3.5				+1	+33/+0.5	-2.4
215	3.0	2.5/2.5	25:1			+1	-6/-2.5	0.0
216	3.0	2.5/2.5	20:1	2800	1540	0	+3/+1.5	+0.5

* RELATIVE UNSUPPRESSED TAKEOFF NOISE AT CONSTANT F_N/W_A = 50 (SINGLE ENGINE PNdB)

The 3.0 BPR/2.5 FPR VCE-201A definition was selected in the engine screening studies as the most promising dual-valve VCE cycle. It was then evaluated with increased amounts of supersonic cruise airflow. Figure 3.1-25 shows the inlet airflow versus Mach number schedule for the representative axisymmetric inlet designed for Mach number 2.4 supersonic cruise. If the inlet capture area is sized for the maximum flow requirement, the operating condition that sizes the inlet is the high bypass ratio mode, such as during either subsonic cruise or take-off. Also shown on Figure 3.1-25 are three engine flow schedules (A, B and C) corresponding to the low bypass mode of operation (turbojet mode). As shown, the B schedule most closely matches the inlet supply at both the subsonic (high BPR mode) and supersonic (low BPR mode) conditions, although even for this best schedule, the inlet/ engine flows are mismatched during the transonic and supersonic climb portions of the mission. At these flight conditions, inlet spillage or bypass losses would adversely affect the installed performance of this engine type.

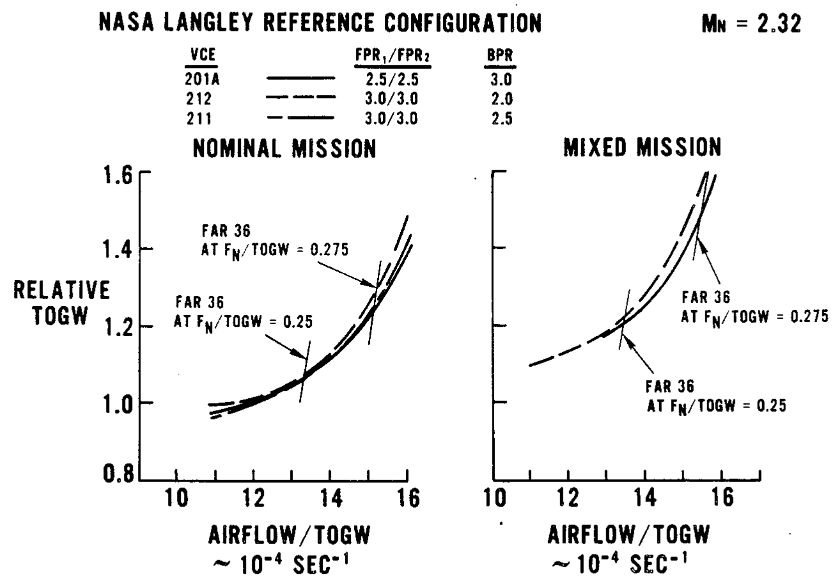


Figure 3.1-24 Cycle Comparison of Dual Valve VCE's

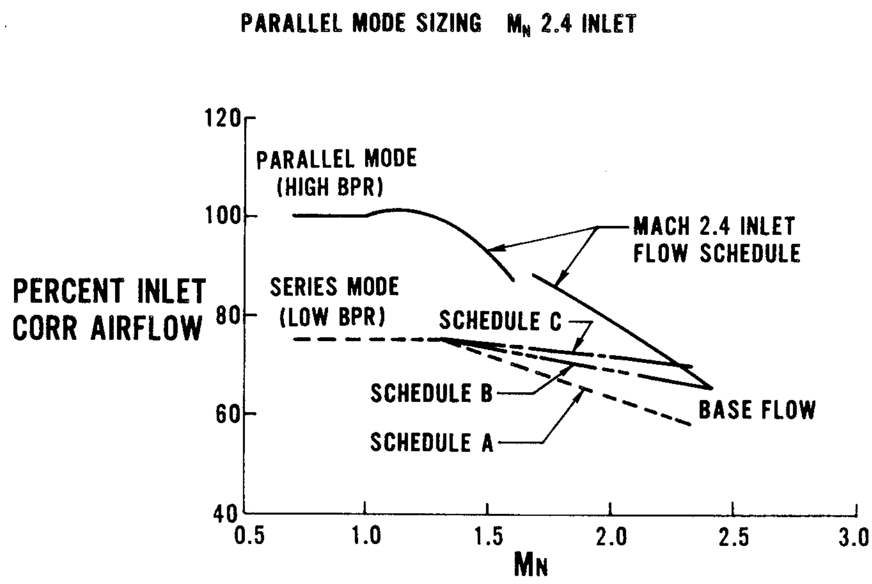


Figure 3.1-25 Dual Valve VCE Inlet Airflow Schedule Matching

As the supersonic cruise inlet corrected airflow is increased, going from schedule A to B to C, the amount of variable fan geometry required is also increased. Increased amounts of variable fan geometry allow the speed of the low spool, and thus the low-pressure turbine stress levels, to be kept to a minimum as the engine corrected airflow is increased. Minimizing the low-rotor speed at the supersonic cruise condition is a critical factor because at this flight conditions the turbine blades and disks are exposed to the most severe combination of stresses, thermal environment (high combustor exit temperature and cooling air temperature) and the highest percent of engine operating time.

Incorporating increased levels of variable fan geometry to minimize rotor speed as the engine airflow schedule is increased, reduces engine weight and design life penalties which would otherwise be associated with these higher supersonic cruise airflow schedules. Even with variable fan geometry, there is still a weight increase. Figure 3.1-26 shows the weight increase with engine airflow at supersonic cruise for the VCE-201 configuration. The benefit of variable fan geometry to minimize low-rotor speed is allowed for in the weight trend shown. Fan surge margin and maximum turbine blade stress levels (design life) were held constant as the flow level was increased.

A comparison of the supersonic cruise performance of the dual-valve VCE-201 engine with these different cruise airflows shows that the intermediate schedule B results in an increase in cruise thrust without a significant change in TSFC (Figure 3.1-27). The higher flow schedule (schedule C) provides a further increase in thrust but with a TSFC penalty. Therefore, schedule B, in addition to matching the inlet flow schedule (Figure 3.1-25), also provides an increase in cruise thrust capability with an improved TSFC.

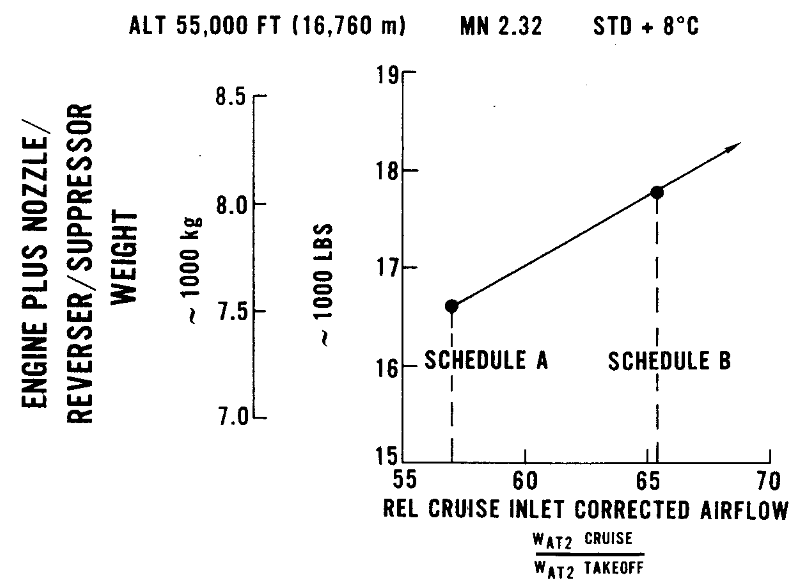


Figure 3.1-26 Supersonic Cruise Engine Weight

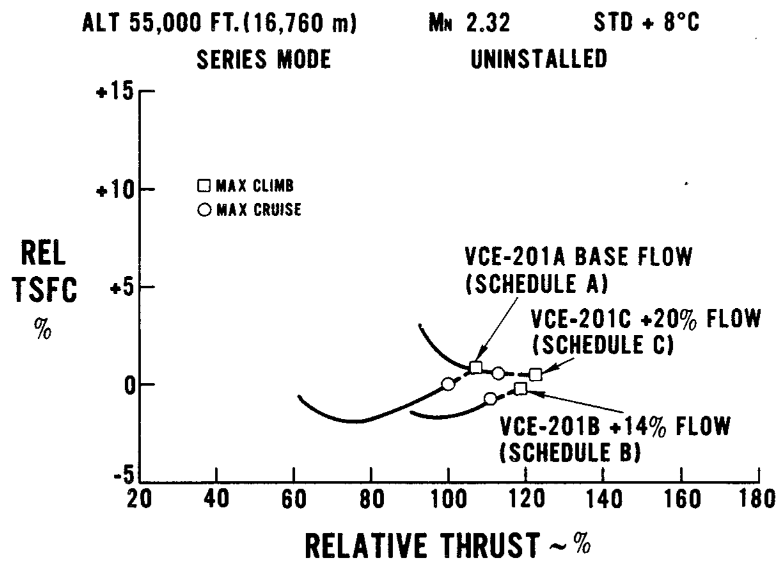


Figure 3.1-27 Dual Valve VCE Estimated Supersonic Cruise Performance

To determine whether the TSFC and cruise thrust improvements offset the increase in engine weight with increasing cruise airflow, the A and B flow schedule versions of the VCE-201 engines were evaluated in terms of relative engine size (airflow/TOGW) and airplane TOGW. The results of this system evaluation (Figure 3.1-28) show that the high flow version, the VCE-201B, yields a lower TOGW at the small values of engine size (low airflow/TOGW), but a higher TOGW at the larger engine sizes. Since there was this sensitivity to engine flow size selection, both the A and B versions of this engine were selected for data-pack definition. In addition, a two stream version (VCE-302B) with similar cycle characteristics, but without the augmentors, was also issued as a data-pack engine. The VCE-302B has the same high flow schedule as the VCE-201B.

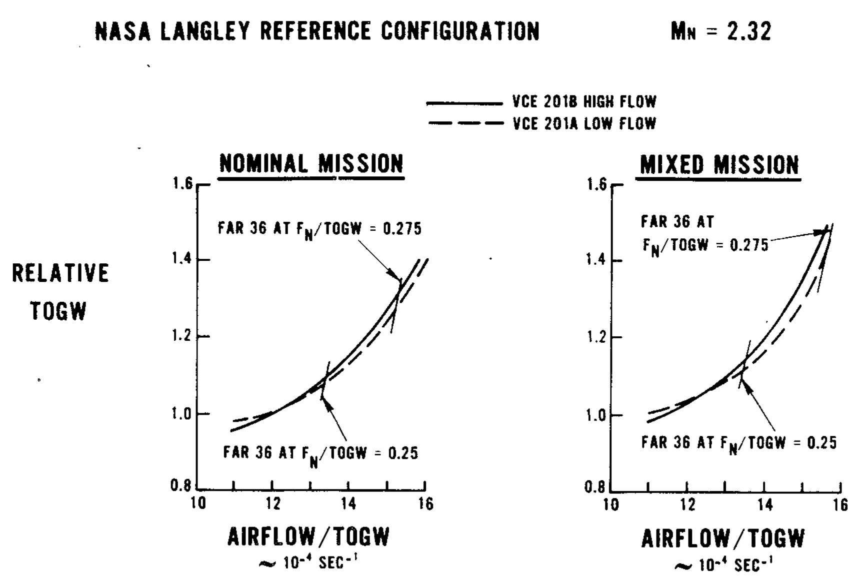


Figure 3.1-28 Comparison of High and Low Flow Dual Valve VCE's

3.1.4 Description of Data-Pack Engines

At the conclusion of the screening studies in which the various types of engines were evaluated parametrically, seven representative engines were selected to be issued in data-pack form to NASA and associated SCAR airframe contractors for a more thorough system evaluation. Data was issued by P&WA in the form of magnetic computer tapes which contained engine performance over the entire flight spectrum. In addition, installation drawings, inlet airflow schedule description, engine weights and envelope dimensions, scaling data and general engine descriptions were included. The following tables and figures summarize the installed engine performance and installation data that were issued in the form of data-pack definitions for each representative engine.

3.1.4.1 Performance Comparison

Table 3.1-VIII contains a summary of the cycle characteristics, basic installation parameters such as engine weights and dimensions, and the date each data-pack was issued. A discussion of the engine weights and dimensions is presented in Section 3.2.1.

TABLE 3.1-VIII

DATA PACK ENGINE WEIGHT AND DIMENSIONS SUMMARY

Engine Identification		LBE-405	VSCE-501	VSCE-502	VCE-107M	VCE-201A	VCE-201B	VCE-302B
Date Issued (1974)		Nov	June 26	June 26	July 31	May 29	May 29	July 2
Mission M_N		2.4 →						
Airflow Schedule		Representative Mach 2.4 Inlet →						
						(Low Flow)	(High Flow)	(High Flow)
Cycle Characteristics (At T.O.)								
Fan Pressure Ratio		4.1	3.3	3.3	2.5/2.5	2.5/2.5	2.5/2.5	2.5/3.0
Bypass Ratio		0.1	2.1	1.3	1.5	3.0	3.0	3.0
Cycle Pressure Ratio		17	15	15	15	20	20	20
Combustor Exit Temp (Max. Climb)	°F	2600	2600	2600	2600	2600	2600	2600
	(°C)	(1430)	(1430)	(1430)	(1430)	(1430)	(1430)	(1430)
Weights								
Bare Engine	lb	13,000	9300	9950	12,650	13,200	14,200	14,100
	(kg)	(5900)	(4220)	(4510)	(5740)	(5990)	(6440)	(6400)
Engine + N/R	lb	15,600	12,400	12,750	15,850	16,600	17,800	17,400
	(kg)	(7080)	(5620)	(5780)	(7190)	(7530)	(8020)	(7890)
Engine + N/R/S	lb	16,800	13,200	13,700	16,850	—	—	—
	(kg)	(7620)	(5990)	(6210)	(7640)	—	—	—
Dimensions								
Nozzle Max Diameter	in.	85.0	91.6	88.8	94.0	88	90	95.0
	(m)	(2.16)	(2.33)	(2.26)	(2.39)	(2.24)	(2.29)	(2.41)
Max Diameter Including Auxiliary Nozzle	in.	—	—	—	—	90	90	—
	(m)	—	—	—	—	(2.29)	(2.29)	—
Eng + N/R Length	in.	301	265	253	303	380	402	413
	(m)	(7.65)	(6.73)	(6.43)	(7.70)	(9.65)	(10.21)	(10.49)

Each of these selected data-pack engine cycles has a potential cruise Mach number capability of 2.7. The cycle for each engine was selected considering not only engine performance but also a compressor discharge temperature limit of 1300°F (700°C) at the maximum Mach number cruise condition (2.7). Since each type of engine has a different OPR lapse between the take-off and supersonic cruise condition, the appropriate OPR at take-off was individually selected for each. As shown by Table 3.1-VIII, all engines were operated at the same maximum combustor temperature, 2600°F (1430°C), and all except the VCE-201A were matched to the same inlet airflow schedule.

Figures 3.1-29 and -30 show the estimated installed supersonic and subsonic cruise performance of the seven engines listed in Table 3.1-VIII. Installed performance includes effects of both internal nozzle performance and external nozzle drag. Performance also includes the effects of the representative Mach 2.4 inlet pressure recovery and drag characteristics.

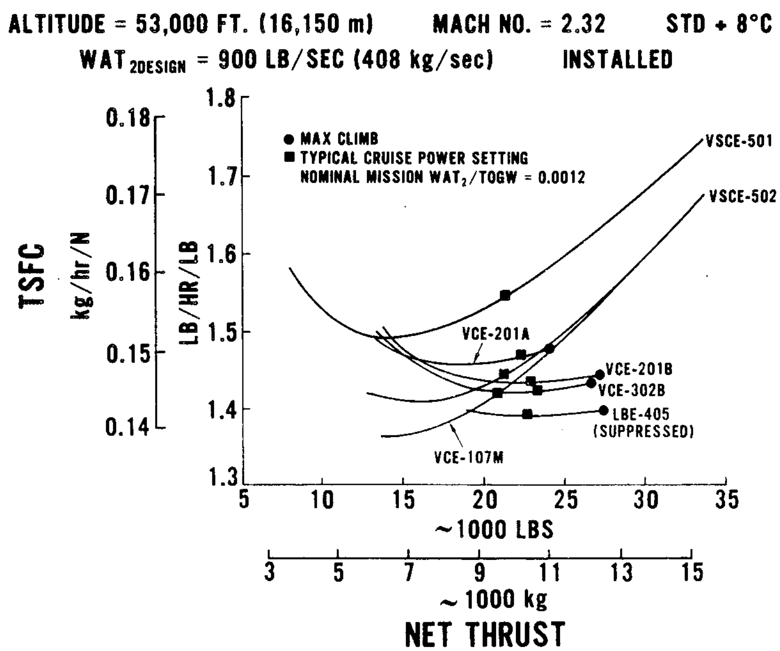


Figure 3.1-29 Supersonic Cruise Performance Comparison of Data-Pack Engines

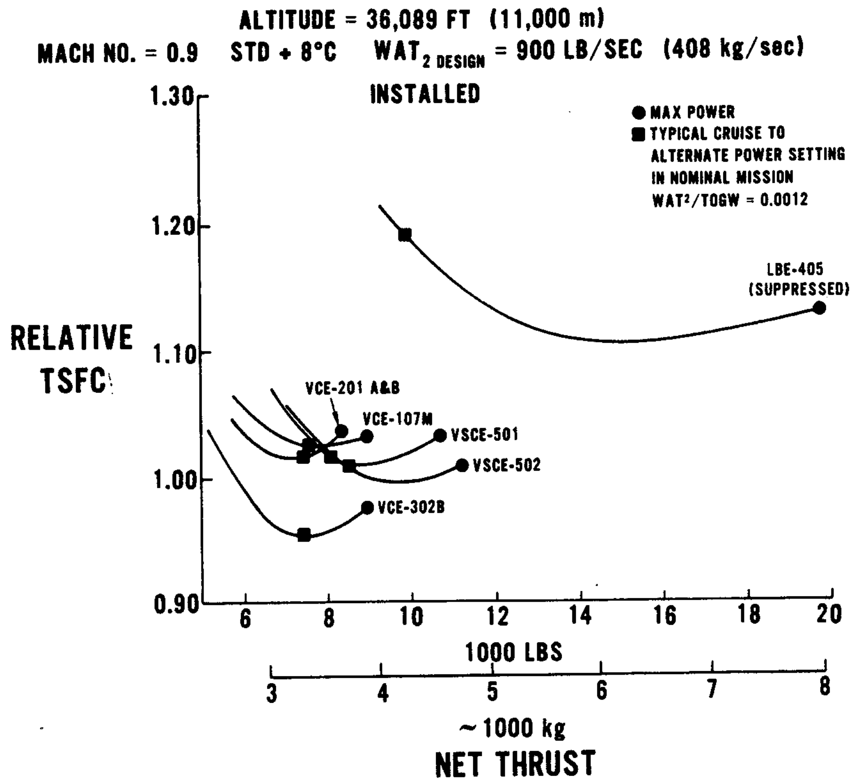


Figure 3.1-30 Subsonic Cruise Performance Comparison of Data-Pack Engines

3.1.4.2 Engine Weights and Dimensions

The engine component technology definition described previously in Section 3.1.2 was utilized to define engine flowpaths for each of the data-pack engines. These flowpaths included: number of fan, compressor and turbine stages; the fan, compressor, burner and turbine diameters; and the engine component lengths. These flowpaths and related engine definition established the overall engine dimensions and provided the basis for preliminary engine weight and cost estimates.

Table 3.1-VIII presents a summary of the engine weights and dimensions for the data-pack engines. As shown by this table, the valves, in conjunction with the additional engine components that constitute the valved VCE concepts, resulted in substantial weight increases relative to the Variable Stream Control Engines. Figure 3.1-31 shows graphically a comparison of the overall dimensions of each basic type of engine.

Since each of the single and dual-valve VCE's have comparable subsonic and supersonic cruise performance levels when compared to the VSCE-502, it would not be expected that these engines would show any overall advantages to the airplane system. Results of P&WA system studies are discussed in Section 3.1.5.

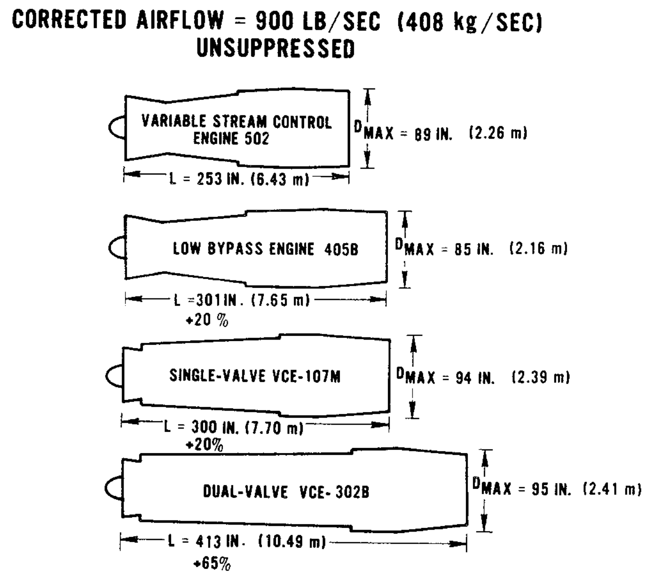


Figure 3.1-31 Overall Size Comparison

3.1.4.3 Data-Pack Engine Price

Relative engine prices are shown in Table 3.1-IX. As indicated, compared to the LBE and VSCE configurations, the single and dual-valve VCE's show significant (60 to 100 percent) increases in engine price.

3.1.5 System Evaluations of Data-Pack Engines

3.1.5.1 P&WA System Evaluation of Data-Pack Engines

Variable Stream Control Engines

During the initial screening of Variable Stream Control Engines, the Inverse Throttle Schedule (ITS) VSCE-502 engine was identified as providing nearly the minimum TOGW airplane when compared to other VSCE's studied. For the purpose of maintaining a reference cycle from the Phase I study, the 2.1 BPR VSCE-501 was updated and redefined for a technology level consistent with the Phase II data-pack engines.

With no change to the basic engine definition, the VSCE-501 and -502 cycles were able to take advantage of the coannular nozzle jet-noise benefit that was being demonstrated in static model tests at about the same time the data-packs were released. The relationship of system sizing parameter (airflow/TOGW) to the take-off thrust loading parameter (Fn/TOGW) and sideline jet-noise goals is shown in Figures 3.1-32 and -33. The left hand curve in Figure 3.1-32 shows the unsuppressed jet-noise characteristic as analytically predicted by the SAE procedure and also as modified for the coannular nozzle noise benefit. Since noise is affected by engine size, data is provided for two airflow sizes. A variable TOGW analysis involves iterations since the engine size isn't known initially.

TABLE 3.1-IX

RELATIVE PRICES FOR DATA PACK ENGINES

Engine Identification	Relative Engine Price
LBE-405B*	Base
VSCE-501	+ 10%
VSCE-502	+ 10%
Single Valve VCE-107M	+ 60%
Dual Valve VCE-201A	+ 90%
Dual Valve VCE-201B	+ 100%
Dual Valve VCE-302B	+ 100%

*including tube suppressor

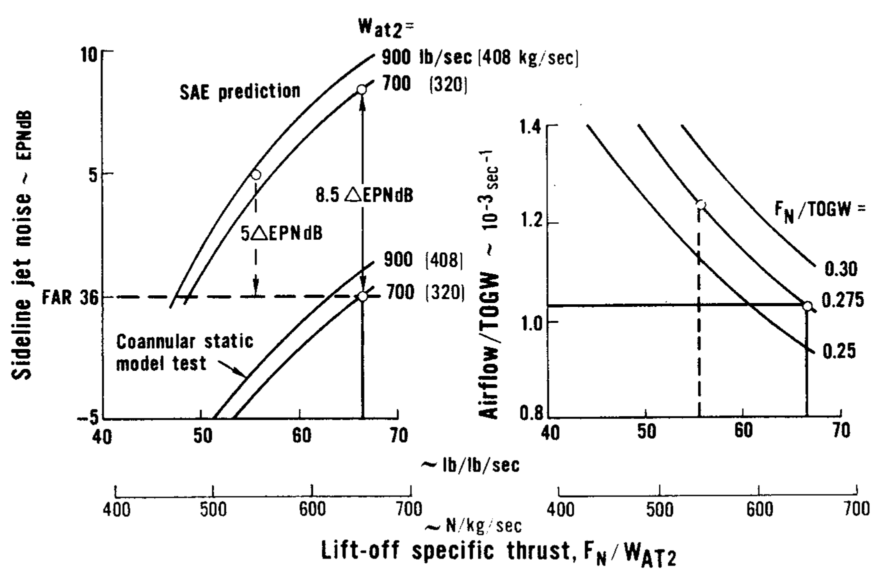


Figure 3.1-32 VSCE Engine Sizing

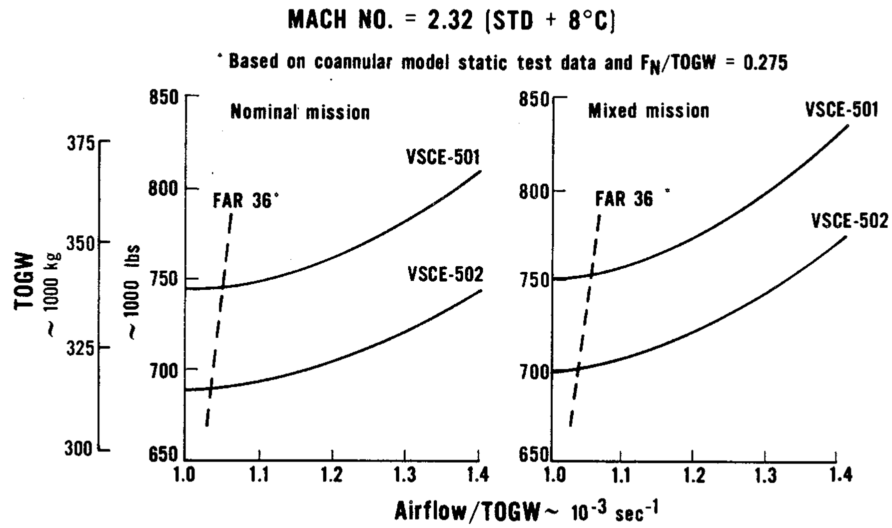


Figure 3.1-33 VSCE-501 and -502 Take-Off Gross Weight Evaluation

For the jet noise to meet FAR 36, the VSCE's can be operated at a lift-off specific thrust of 66.5 lb/lb/sec (650 N/kg/sec) assuming a coannular noise benefit of 8.5 EPNdB at this operating condition. The right hand curve in Figure 3.1-32 indicates that the corresponding engine aiflow size parameter (airflow loading) is 0.00103 sec^{-1} for a 0.275 lift-off thrust loading. If the lift-off specific thrust is reduced to 55.5 lb/lb/sec (540 N/kg/sec), the sideline noise would be reduced to FAR 36 minus 3 EPNdB; or, if in flight, the coannular benefit decreases to 5 EPNdB, the 55.5 lb/lb/sec (540 N/kg/sec) specific thrust would just meet FAR 36. The corresponding airflow size parameter would then be 0.00124 sec^{-1} at a lift-off thrust loading of 0.275 (or 0.00113 sec^{-1} at a thrust loading of 0.25). As will be seen in the next figure, these airflow size parameter values are low enough to provide near minimum TOGW for VSCE's.

The evaluation of VSCE-501 and -502 is shown as a function of the engine airflow size parameter in Figure 3.1-33. The engine size required for FAR 36 sideline jet noise, applying the coannular benefit, is indicated. At this engine airflow size, the TOGW is essentially at the minimum value for both engines. The results show that the VSCE-502 is significantly better than the VSCE-501 for both the nominal (all supersonic), and mixed missions. The left side of these curves are relatively flat, indicating that a moderate increase in the airflow parameter does not result in a large TOGW penalty. This characteristic is very important if jet noise levels less than FAR 36 are required or if the full statically measured coannular noise benefit cannot be achieved in flight. The results for the mixed mission show that the VSCE's are well balanced in their subsonic and supersonic cruise efficiencies in the NASA Reference Airplane Configuration, with the mixed mission being only slightly more critical than the all supersonic mission.

Figure 3.1-34 presents a fuel consumption comparison, expressed in relative TOGW decrease vs. distance for the all supersonic mission. This curve provides an indication of the fuel burned during each leg of the mission. Since acceleration characteristics of these engines differ, climb fuel alone does not provide a good indication of the engine's climb characteristics. Starting at zero distance, both airplanes are at their maximum TOGW. The first segment is the subsonic climb to Mn 0.9. Both the VSCE-501 and -502 are essentially equal. During the second leg, the acceleration to supersonic cruise speed, the average fuel consumption is lower for the -502, as indicated by the shallower slope in that segment. Up to the start of supersonic cruise, the VSCE-502 has consumed less fuel than the 501. During the supersonic cruise, the VSCE-502 again has a lower average fuel consumption (better range factor) than the 501, as indicated by the shallower slope. By the end of descent, the VSCE-502 has consumed significantly less fuel than the 501, and this difference is preserved when the reserve fuel is included. Since the relative engine weights are about the same in this case, the higher zero fuel weight (ZFW) for the VSCE-502 translates into more payload or lower TOGW as shown in Figure 3.1-33. The economic evaluation for the 2500 nm (4630 km) average mission is shown in Figure 3.1-35. The VSCE-502 shows significant advantages over the VSCE-501 in both ROI and DOC.

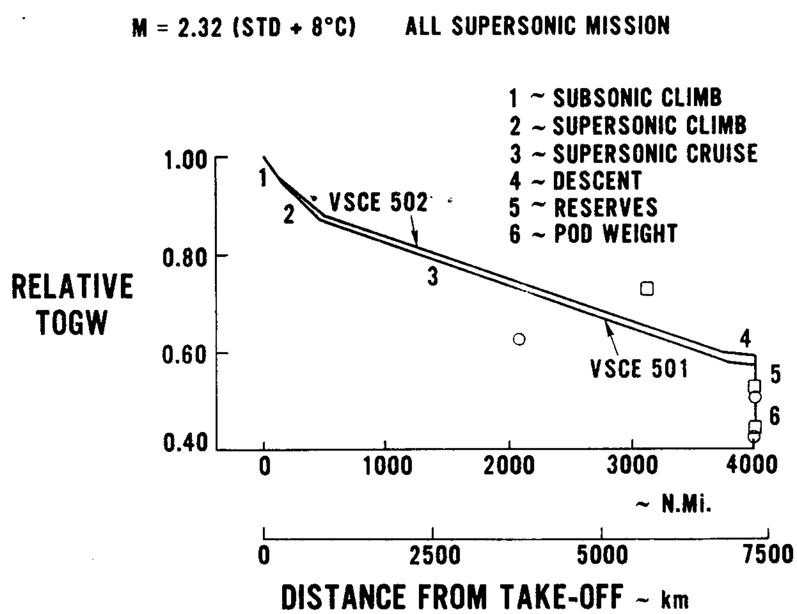


Figure 3.1-34 VSCE-501 and -502 Fuel Consumption Comparison

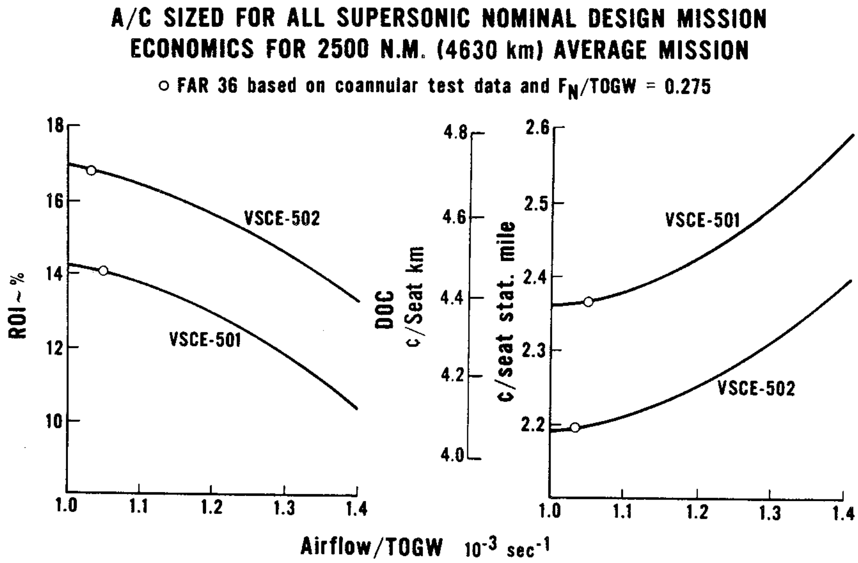


Figure 3.1-35 Economic Comparison of VSCE-501 and -502

Low Bypass Engines (LBE-405)

The screening studies of Low Bypass Engines (LBE) indicated that the non-augmented 0.1 BPR LBE-405 provided the lowest TOGW. Since the LBE's have a relatively high weight/airflow characteristic, they are competitive only when they can be matched to minimum airflow levels which require high levels of jet-noise suppression. The engine sizing factors are shown in Figure 3.1-36. These curves are analogous to those used for the VSCE's except that relative jet velocity is used for the abscissa rather than specific thrust. This is preferred because jet-noise suppressor characteristics are more easily related to jet velocity and because the jet-noise level is independent of suppressor thrust losses for a given jet velocity. The relative jet velocity and the corresponding exhaust gas temperature are for the mixed core-and-bypass flow. With the multi-tube suppressor characteristics shown in Figure 3.1-7, jet-noise levels can meet FAR 36 with a relative jet velocity of 2400 ft/sec (730 m/sec) which corresponds to about 2700 ft/sec (820 m/sec) absolute jet velocity. At this condition, 14.2 EPNdB of suppression is required to meet FAR 36. The corresponding airflow size parameter is 0.001045 sec^{-1} at a thrust loading of 0.275 and includes an 11.5% suppressor thrust loss. If the suppressor can only achieve 10 EPNdB of suppression with the same thrust loss, the engine would have to operate at a take-off power setting equivalent to a relative jet velocity of 2100 ft/sec (640 m/sec). The corresponding airflow size parameter would then be 0.0012, which would translate into a significant TOGW penalty.

Figure 3.1-37 shows the impact of suppressor thrust losses on the required airflow size parameter. The multi-tube suppressor assumed an 11.5 percent loss in gross thrust at 200 knots (370 km/hr) at 2400 ft/sec (730 m/sec) relative jet velocity. This corresponds to a specific thrust of 66 lb/lb/sec (650 N/kg/sec). If the suppressor gross thrust loss could be reduced to 6 percent and the engine operated at 2400 ft/sec (730 m/sec) (FAR 36), the specific thrust would increase to 70.6 lb/lb/sec (690 N/kg/sec) and the airflow size parameter would be reduced to 0.00097. The suppression level required, however, would be the same (i.e., 14.2 EPNdB).

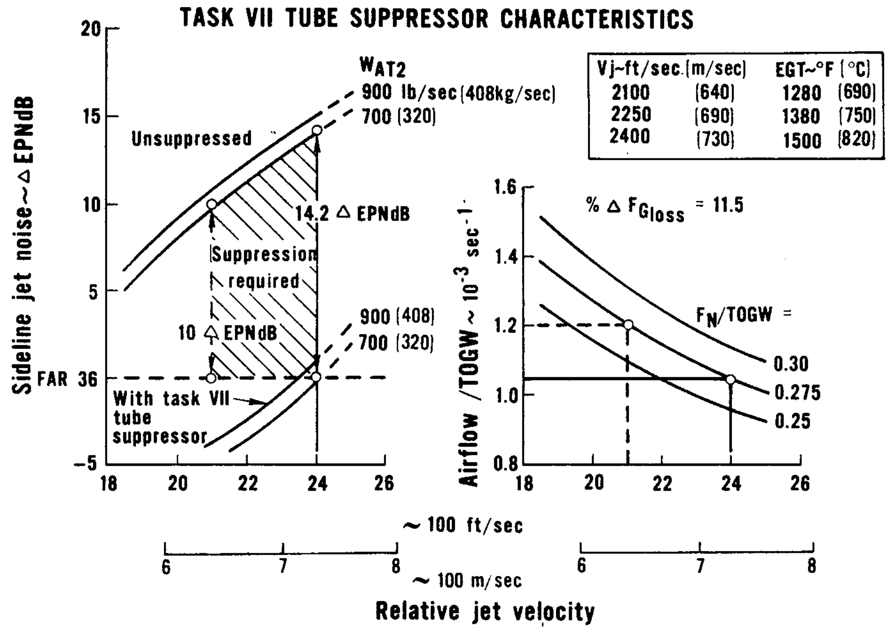


Figure 3.1-36 Low Bypass Engine Sizing for Take-Off

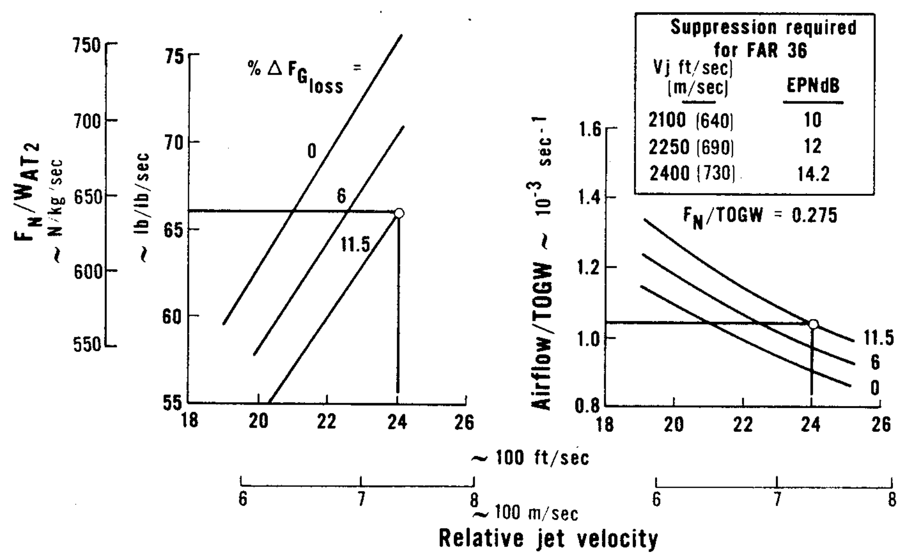


Figure 3.1-37 Effect of Suppressor Thrust Loss on LBE Sizing

The TOGW evaluation of the LBE-405 is shown as a function of the airflow size parameter in Figure 3.1-38. The solid line is for an unsuppressed LBE-405. The dashed curve includes the weight of the suppressor plus an estimated 1 percent penalty in nozzle Cv at all flight conditions because of the effect the stowed, multi-tube suppressor has on the nozzle design. The dash-dot curve includes the suppressor weight penalty but assumes no loss in nozzle performance. Without a suppressor, the engine size required for LBE-405 jet noise to meet FAR 36 is unacceptably large. With the assumed multi-tube suppressor, the TOGW is competitive with the VSCE-502 for the all supersonic mission. The LBE-405, however, is not as competitive for the mixed mission. Note the steepness of the LBE-405 TOGW curve with increasing airflow size. This indicates the LBE's sensitivity to good suppressor performance. The dashed curve, which includes a nozzle penalty for the suppressor, represents the baseline LBE-405 performance.

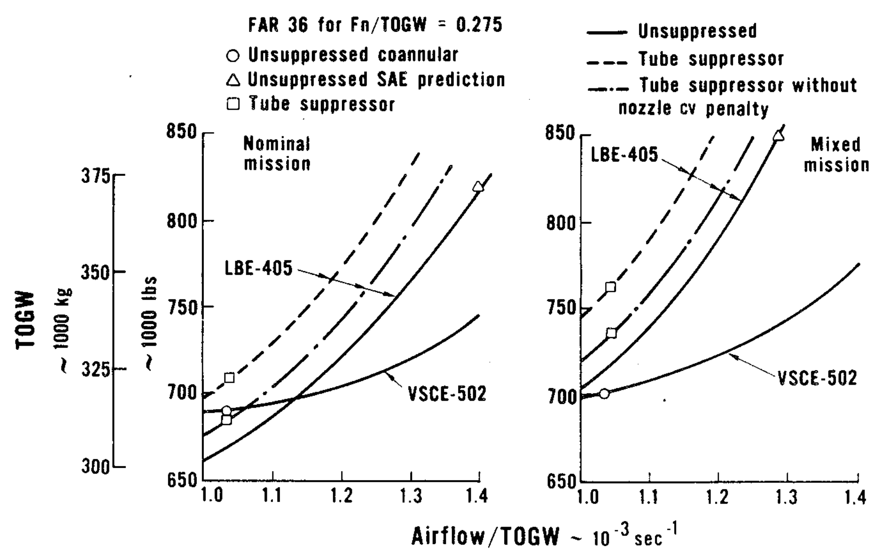


Figure 3.1-38 LBE-405 Take-Off Gross Weight Evaluation

The impact of the jet suppressor on the TOGW vs. noise relationship for LBE-405 is shown in Figure 3.1-39. The dashed line (1) represents the TOGW vs. noise relationship without a suppressor. Line (2) includes the weight and performance losses associated with the suppressor, but does not include the suppressor noise reduction. The noise increase is due to the higher power setting required to regain the thrust loss from the suppressor. Line (3) is similar to line (2) except it includes the suppressor noise reduction. It can be seen that the net suppressor benefit is only about half of that expected without the weight penalty and performance loss.

Figure 3.1-40 presents the relative fuel consumption with distance for the LBE-405 and the VSCE-502 on the all supersonic design mission. The LBE-405 accelerates at a higher average rate than the VSCE-502 during the subsonic climb, and at about the same average rate during the supersonic climb. The VSCE-502 is not operated at its maximum augmentation level during climb, but at a level optimized for best range. The LBE-405 reaches its begin-cruise altitude while the VSCE-502 is still climbing. This results in the LBE-405 having consumed less fuel at the same distance as the VSCE-502 at begin cruise. If the supersonic climb drag is higher than predicted, however, the performance of the LBE-405 will be degraded more than the VSCE-502 which has the flexibility of increasing its augmentation level. The LBE-405 has a better cruise range factor than the VSCE-502, which, coupled with the initial climb advantage, translates into an advantage in fuel consumed at the end of descent. However, the higher reserve fuel weight required for the LBE-405 and its higher engine weight off-set this advantage.

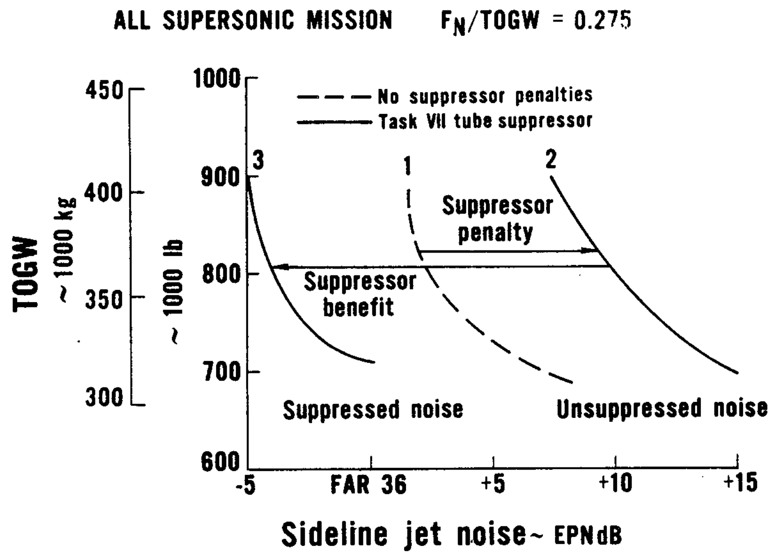


Figure 3.1-39 Effect of Suppressor on LBE-405 TOGW vs. Noise

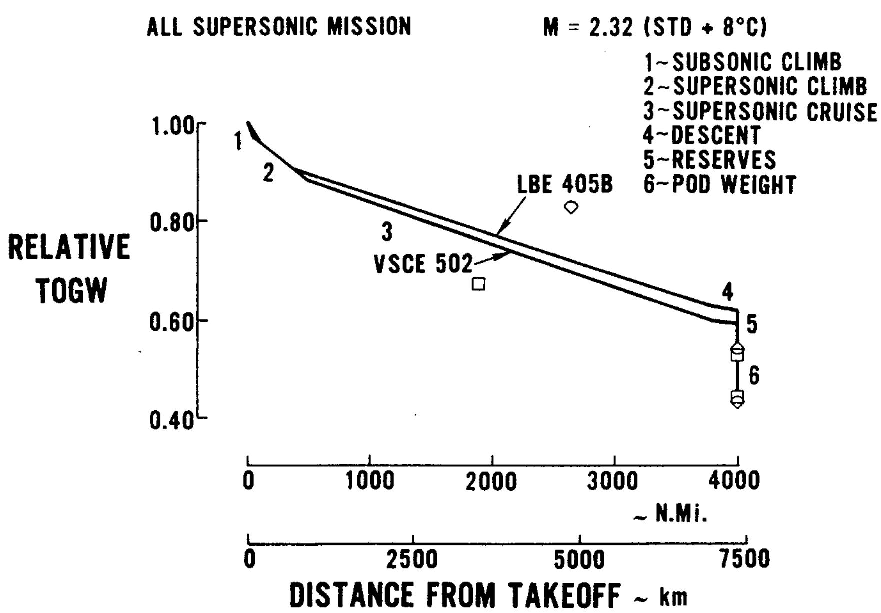


Figure 3.1-40 LBE-405B and VSCE-502 Fuel Consumption Comparison

The economic evaluation of the suppressed LBE-405 for the 2500 nm (4630 km) average mission is shown in Figure 3.1-41. The LBE is not as attractive as the VSCE-502 on either an ROI or DOC basis because the subsonic leg in the average mission significantly degrades the fuel consumption performance of the LBE-405.

Valved Variable-Cycle Engines

Figure 3.1-42 shows the TOGW vs. airflow size parameter results for the valved VCE's compared to the VSCE-502. The dual-valve VCE-201B resulted in the lowest TOGW of all of the dual-valve engines evaluated. The higher TOGW of the dual-valve VCE-201A resulted from its lower supersonic flow capacity relative to the VCE-201B. Another dual-valve engine, the VCE-302B (not shown in Figure 3.1-42), had insufficient climb thrust for reasonable engine sizes and, as a result, it could not achieve the design range of 4000 nm (7400 km) with a reasonable TOGW. The VCE-107M, a single-front-valve engine, resulted in a lower TOGW than the dual-valve engines but was still not competitive with the VSCE-502.

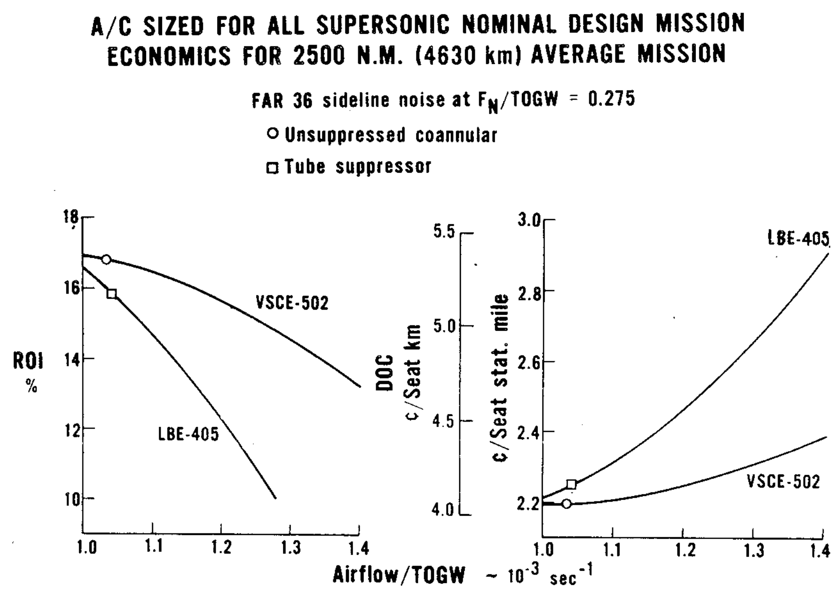


Figure 3.1-41 Economic Comparison of LBE-405 and VSCE-502

The reason that the valved VCE's are not competitive is that at the operating cruise power setting the TSFC's are only slightly lower than that of VSCE-502 and the weights are significantly higher. For the comparison shown in Figure 3.1-42, the engines are sized for jet noise levels that meet FAR 36 assuming that all of these valved engines can take advantage of the coannular noise benefit.

Although this initial study did not result in a competitive VCE concept, the study did reveal areas of deficiencies and suggested possible improvements. As a result, refined versions of the valved engines were defined. One of these was studied late in the Phase II effort and showed significant improvement relative to the data-pack valved engine concepts. This rear-valve concept is discussed in Section 3.2.

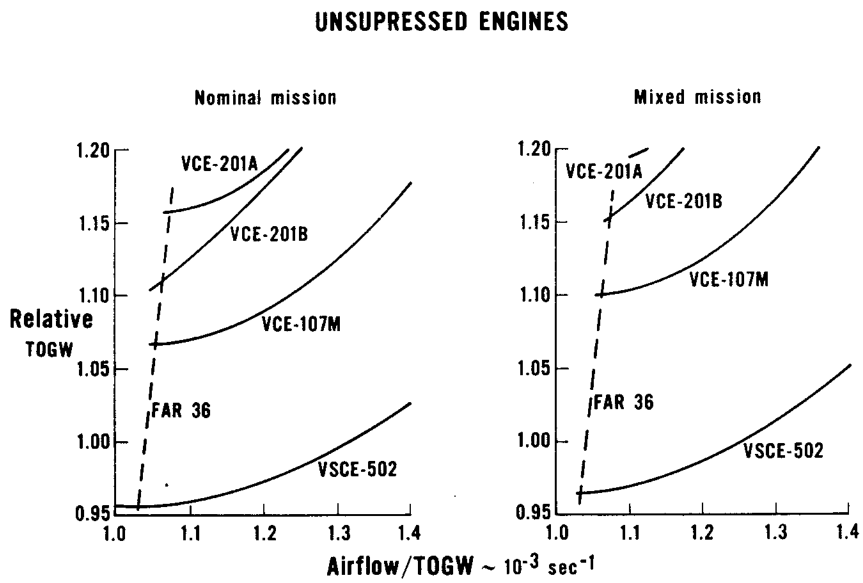


Figure 3.1-42 Valved-VCE and VSCE Comparison

Data-Pack Engine Summary Comparisons

Figure 3.1-43 presents a TOGW versus noise summary comparison of the data-pack engines for the all supersonic mission. This comparison shows the unsuppressed VSCE-502 with coannular noise benefits to be the best of the data-pack engines. It provides the lowest TOGW at FAR 36 jet noise levels and exhibits minimum penalty in TOGW as the jet-noise level is reduced. The coannular noise benefit has the potential for substantial reductions in noise relative to the SAE prediction. The LBE-405 with the assumed multi-tube suppressor is competitive with the VSCE-502 at FAR 36, but its TOGW increases rapidly as the noise level is reduced. The LBE-405 without this very effective suppressor is not competitive. The dual-valve and single-front-valve VCE's have significantly higher TOGW's than the VSCE-502 even when credited for the same coannular noise benefit.

An ROI comparison of these engines is shown in Figure 3.1-44. These airplanes were sized for the all supersonic design mission, but the economics were evaluated on the 2500 nm (4630 km) average mission. The engine comparison on this economic basis gives essentially the same results as the TOGW comparison.

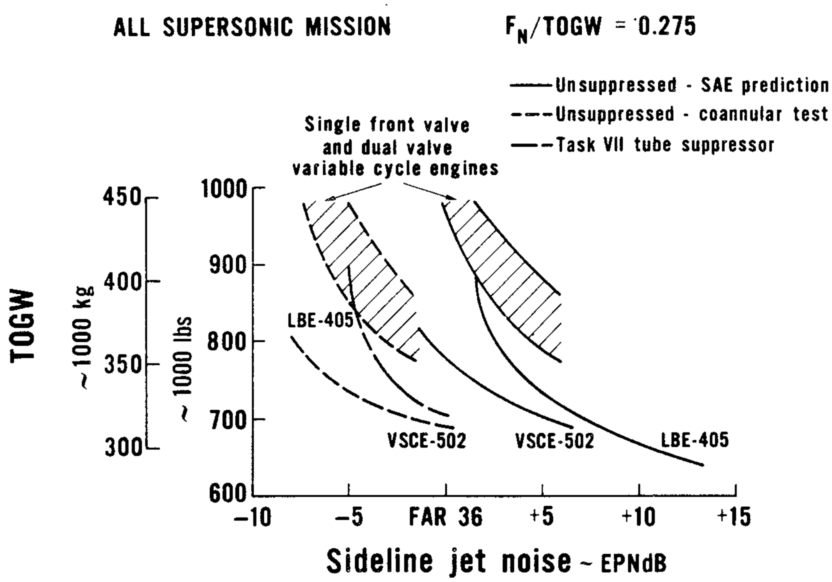


Figure 3.1-43 Engine Comparison Summary

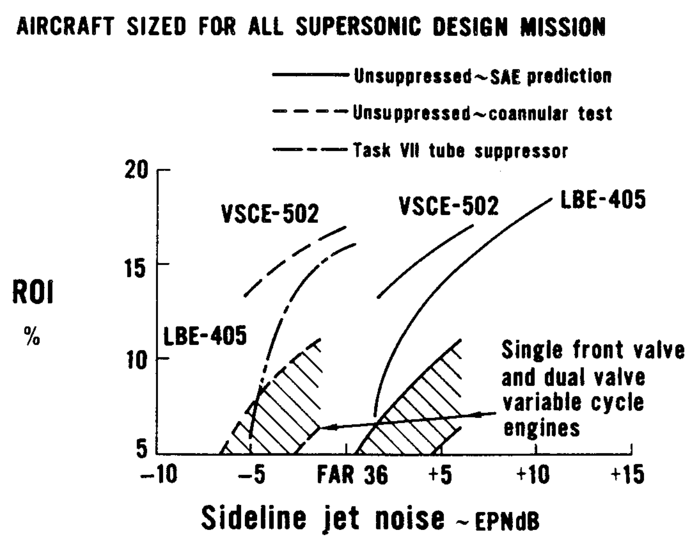


Figure 3.1-44 Engine Economic Comparison Summary

3.1.5.2 Boeing System Evaluation of Data Pack Engines

Pod Geometry and Drag Data

Pod geometries were developed for selected data-pack engine definitions. Figure 3.1-45 shows a typical pod geometry definition for the VSCE-502 from which area distributions and pod drags were calculated. Figures 3.1-46 and -47 show the pod cross-sectional area versus length and the pod drag versus Mach number for four of the engines subjected to airplane performance analysis. One of these engines is a representative P&WA engine from the Phase I study, the D/H TF C-D (Duct-Heating Turbofan having a 2.1 BPR). It was included as a reference to measure improvements of VCE concepts. The drag data for the VCE-107M (Figure 3.1-46) is quite optimistic, since no allowance was made for the engine accessories envelope. The geometry of the engine is such that the accessories package would create prohibitive drags. In order to determine if the cycle was otherwise competitive, the pod was defined without consideration for accessories.

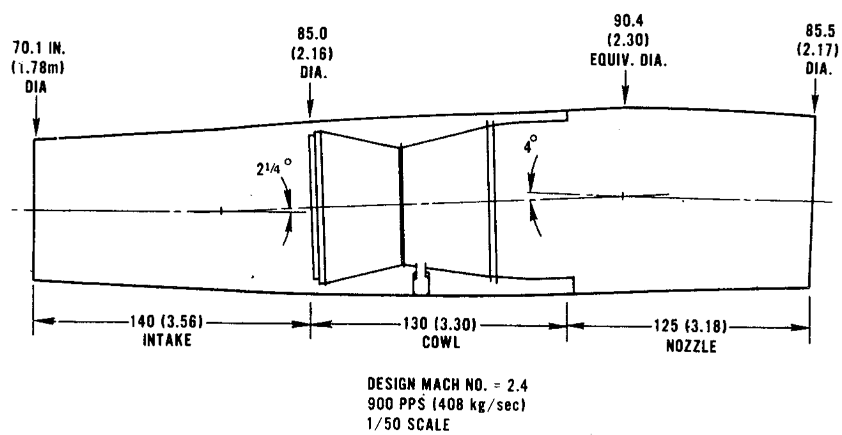


Figure 3.1-45 VSCE-502 Engine Pod

Pod Weight Data

Baseline propulsion pod weight data is shown in Table 3.1-X. Figure 3.1-48 indicates the pod weight trend versus engine size. A 20% reduction in engine size provides a pod weight reduction in the order of 9000 lb (4080 kg) for the entire airplane. These data reflect pod weight differences only; vertical tail size, gear lengths, wing flutter, material, balance, etc. have not been included. For a given configuration, the inclusion of these effects would accentuate the gains shown in Figure 3.1-48.

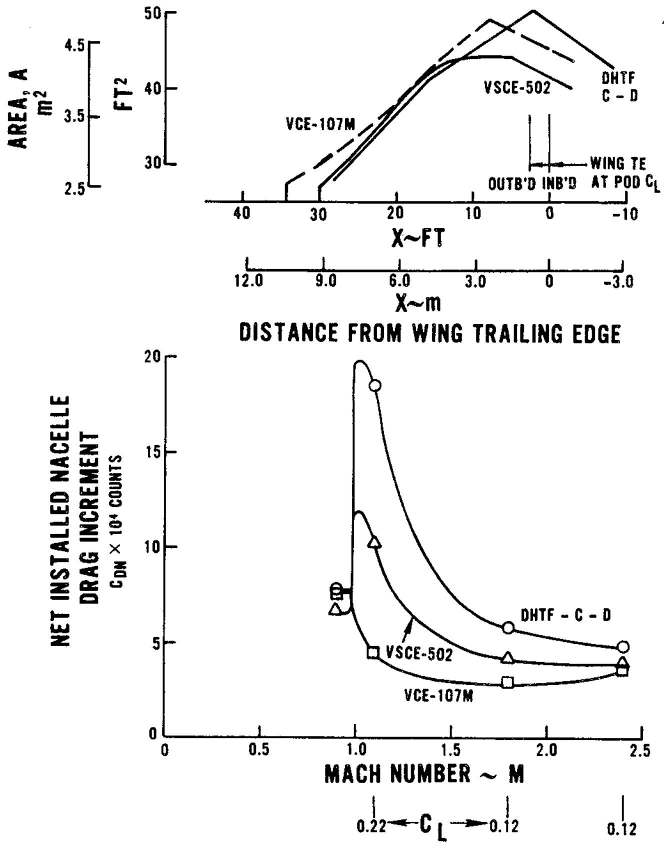


Figure 3.1-46 Pod Drag and Geometry for DHTF D-C, VCE-107M and VSCE-502

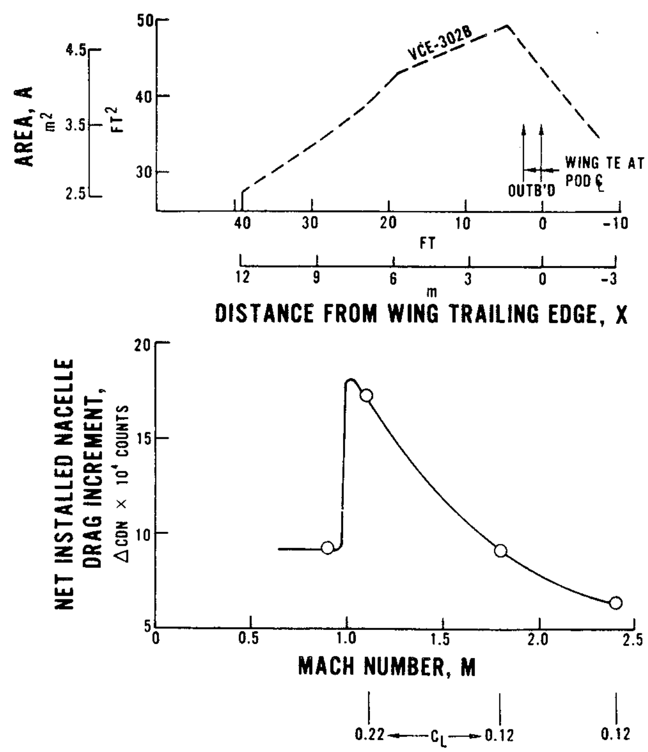


Figure 3.1-47 Pod Drag and Geometry for VCE-302B

TABLE 3.1-X

POD WEIGHT DATA ~ lb (kg)
BASE AIRFLOW 900 PPS (408 kg/sec) @ SLS (HIGH BYPASS MODE FOR VALVED VCE'S)

	VCE-201A	VCE-302A	VCE-302B
Engine	16600 (7530)	16200 (7350)	17400 (7890)
Inlet	3380 (1530)	3430 (1560)	3430 (1560)
Cowl	1750 (790)	1740 (790)	1740 (790)
Supt	1130 (510)	1110 (500)	1170 (530)
Total/Pod	22860 (10370)	22480 (10200)	23740 (10770)
/Airplane	91440 (41480)	89920 (40790)	94960 (43070)

	D/HTF C-D	VSCE-502	VSCE-502 (Suppressor In Bypass Stream)	VCE-107M
Engine	12260 (5560)	12750 (5780)	13700 (6210)	15850 (7190)
Inlet	3760 (1700)	3460 (1570)	3460 (1570)	3530 (1600)
Cowl	1220 (550)	860 (390)	840 (380)	1410 (640)
Supt	830 (380)	890 (400)	940 (430)	1080 (490)
Total/Pod	18070 (8190)	17960 (8150)	18940 (8590)	21870 (9920)
/Airplane	72280 (32785)	71840 (32590)	75760 (34360)	87480 (39680)

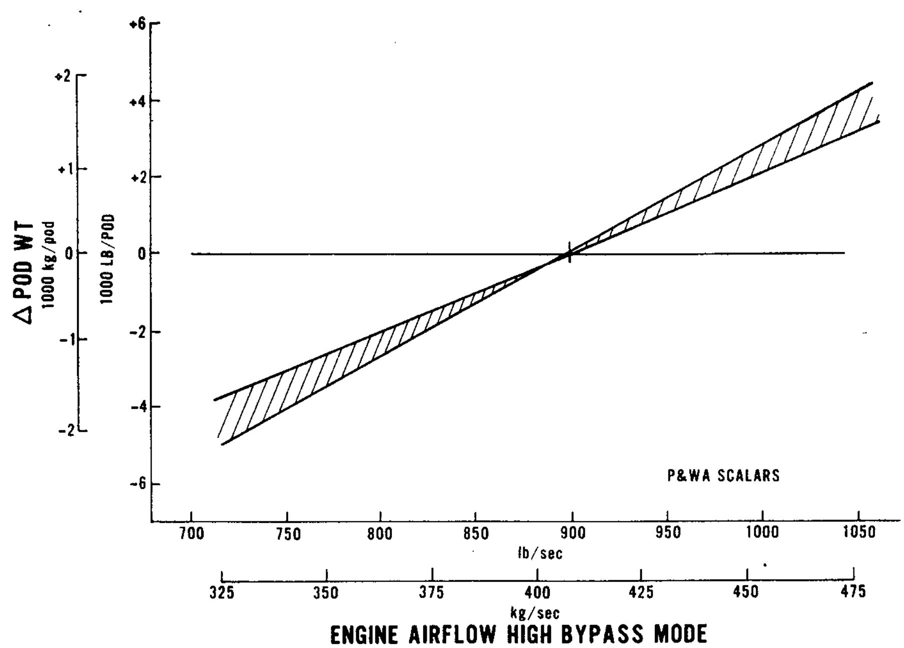


Figure 3.1-48 Pod Weight Trend as a Function of Engine Size

Comparative Airplane Performance

The results of the Boeing performance evaluation of the various data-pack engines for the baseline airplane configuration are presented in this section. Table 3.1-XI contains a summary of climb match data, range increments and mission fuel buildups for 900 lb/sec (408 kg/sec) size engines. The effect of engine size, subsonic legs, and reduced noise on airplane range are also presented.

A comparison of the installed performance of the VSCE-502 with the Phase I engine, the D/H TF C-D, is included in Table 3.1-XI, and the effect of engine size is shown in Figure 3.1-49. Two range values are given in Figure 3.1-49 for the VSCE-502 at an engine size of 900 lb/sec (408 kg/sec). The lower value uses the same propulsion pod weight and drag levels as the C-D cycle and thus reflects the significant improvements in thermodynamics. The second value includes the correct weight and drag level for the VSCE-502. The reduced propulsion pod drag provides an additional benefit of 43 nautical miles (80 km) plus the reduction in propulsion weight of 110 pounds (50 kg) per pod, which is equivalent to 8 nautical miles (14.8 km), and leads to a total improvement of 346 nautical miles (640 km) for the 900 lb/sec (408 kg/sec) engine size over the D/H TF C-D. Most of this range improvement is due to better cruise TSFC, (1.498 lb/hr/lb (0.153 kg/hr/N), compared to 1.604 (0.164) for the D/HTF C-D. The effect of engine size for the VSCE-502 shown in Figure 3.1-49 indicates an engine size between 800 and 850 lb/sec (360 and 380 kg/sec) would be optimum and would increase the range improvement to 370 nautical miles (685 km).

The range and thrust margin characteristics of the dual-valve engines are shown in Figure 3.1-50. The initial data-pack definition of the nonaugmented VCE-302B (identified as Base in Figure 3.1-50) was found to be deficient in climb thrust. This deficiency, plus its excessive weight resulted in poor range capability, -300 nautical miles (560 km), relative to the D/H TF C-D. Discussions with P&WA of possible improvements led to the following revisions to this engine:

Revisions	
1	Hotter CET for supersonic climb (Mn 1.3 to 1.9)
2	Hotter CET for transonic climb (Mn 1.1)
3	A weight reduction of 2000 pounds (910 kg) per engine based on a reconfigured valve arrangement

These revisions were evaluated for effects on range and, as indicated in Figure 3.1-50, increased the VCE-302B range by approximately 300 N.Mi (560 km). However, even with these revisions, the dual-valve engine has range capability that is no better than the Phase I D/H TF C-D. The augmented version of the dual-valve engine VCE-201B, was judged to be no better, as shown in Figure 3.1-50.

TABLE 3.1-XI

RANGE INCREMENTS AND MISSION FUEL BUILD-UPS

$W_{a_{SLS}}$ = 900 LB/SEC

MTW = 750,000 lb PL = 57057 lb (273 Pass) STD + 8°C Day M_{cruise} = 2.32 Baseline Airplane	Phase I Duct-Heating Turbofan DHTFC-D	VSCE VSCE-502		Dual-Valve VCE's VCE-201B		VCE-302B		VCE-302BIM		Single Front-Valve VCE-107M	
Total Mission Range Increment, nmi	0	+346		−61		−435		−18		+48	
Engine Plus Pod Weight, lb	18070	17960		22860		23740		21740		21870	
OEW, lb	344200	343760	+8	363360	−316	366880	−374	358880	−242	359400	−250
Taxi & Takeoff Fuel, lb	7107	6446	+7	6136	+11	5864	+14	5788	+15	6446	+7
Subsonic Climb Fuel, lb	24286	19216	+14	27825	−34	23802	−36	23806	−36	22922	−13
Distance, nmi	115	73		121		74		74		87	
Supersonic Climb Fuel, lb	62106	52729	+43	72566	−61	136140	−430	93602	−143	60876	−21
Distance, nmi	309	249		372		798		547		275	
Cruise @ W = 550k lb L/D	7.955	8.19	+258	8.18	+325	8.04	+311	8.045	+314	8.14	+302
TSFC lb/hr/lb	1.60	1.50		1.455		1.445		1.445		1.47	
Descent Plus ILS Fuel, lb	4489	4366	+8	4459	+11	5336	−2	5503	−8	4445	+8
Distance, nmi	176	182		186		188		185		183	
Reserves Fuel, lb	49371	48882	+8	49190	+3	44361	+82	44379	+82	48431	+15
$RF_M = 0.9/RF_M = 2.32$	1.09	1.03		0.95		1.03		1.03		0.97	

Mach Number	T-D D	P.S.	T-D D	P.S.	T-D D	P.S.	T.D D	P.S.	T.D. D	P.S.	T.D. D	P.S.
M = 0.9	0.245	2	0.685	14	0.531	63	0.982	20	0.982	20	0.410	64
1.1	0.477	1	0.466	12	0.511	61	0.061	20	0.215	20	0.573	11
1.6	0.633	1	0.559	12	0.333	12	0.089	20	0.237	20	0.482	12
2.32	0.128	1	0.581	12	0.444	12	0.325	20	0.270	20	0.560	12

c-2

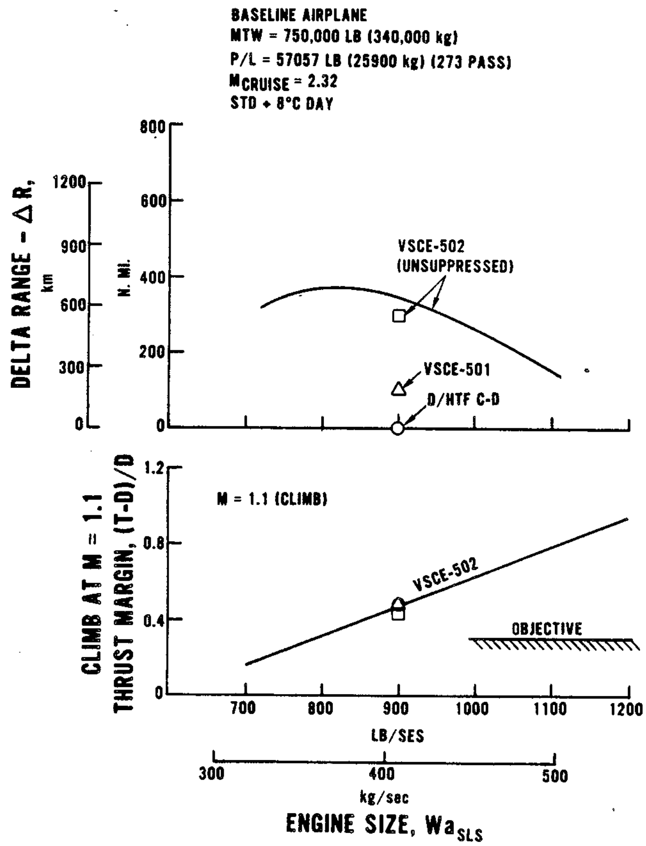


Figure 3.1-49 Effect of Engine Size on Range and Thrust Margin for VSCE Cycles

Figure 3.1-50 also shows the performance characteristics of the single-valve VCE-107M. At 900 lb/sec (408 kg/sec) size, it has only 48 nautical miles (89 km) more range than the D/H TF C-D, even with the optimistic pod geometry that excluded dimensional effects of accessories. The improvement of 302 nautical miles (560 km) in cruise performance for this front-valve engine is negated by the increase in propulsion pod weight, 3800 lb (1720 kg), per pod with a corresponding 250 nautical mile (460 km) decrease. As shown in Figure 3.1-50, the VSCE-502 was identified as the best data-pack engine evaluated in these parametric integration studies.

The performance evaluations of these valved VCE concepts for the Boeing baseline airplane configuration led to the conclusion that the single front-valve and the dual-valve concepts were not competitive because of excessive weight, poor climb performance, and relatively high propulsion pod drag.

At this point in these integration studies, it was decided to concentrate on a new valved engine concept, the single rear-valve VCE, that was designed to overcome these problems. This new concept evolved from these initial parametric studies and is described in the next section, along with an improved version of the VSCE-502 concept.

TABLE 3-1-XI

RANGE INCREMENTS AND MISSION FUEL BUILD-UPS (SI UNITS)

$W_{A_{SLS}} = 408$ kg/sec

MTW = 340193 kg PL = 25880 kg (273 Pass.) STD + 8°C Day $M_{cruise} = 2.32$ Baseline Airplane	Phase I DHTFC-D	VSCE-502		Dual-Valve VCE's VCE-201B		Dual-Valve VCE's VCE-302B		Dual-Valve VCE's VCE-302BIM		Front Single Valve VCE-107M	
Total Mission Range Increment, km	0	+641		−113		−806		−33		+89	
Engine Plus Pod Weight, kg	8050	7800		10180		10570		9680		9740	
OEW, kg	153290	153090	+15	161830	−585	163390	−693	159830	−448	160060	−463
Taxi & Take-off Fuel, kg	3160	2870	+13	2730	+20	2610	+26	2580	+28	2870	+13
Subsonic Climb Fuel, kg	10820	8560	+26	12390	−63	10600	−65	10600	−65	10210	−24
Distance, km	210	130		220		140		140		160	
Supersonic Climb Fuel, kg	27660	23480	+80	32320	−113	60630	−796	41690	−265	27110	−39
Distance, km	570	460		690		1480		1010		510	
Cruise @ W = 249475 kg L/D	7.950	8.19	+478	8.18	+602	8.04	+576	8.045	+582	8.14	+599
TSFC kg/hr/N	0.160	0.150		0.148		0.148		0.148		0.150	
Descent Plus ILS Fuel, kg	1200	1940	+15	1980	+20	2380	−4	2450	−15	1980	+15
Distance, km	330	340		340		350		340		339	
Reserves Fuel, kg	21990	21770	+15	21910	+6	19760	+152	19760	+152	21569	+28

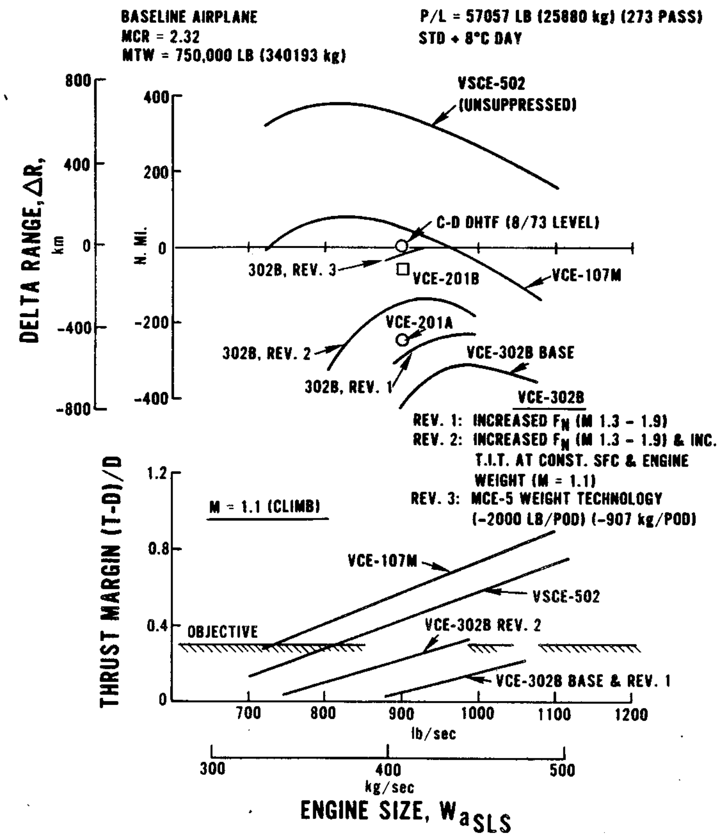


Figure 3.1-50 *Effect of Engine Size on Range and Thrust Margin for Selected Data-Pack Engines*

3.2 REFINED STUDIES

3.2.1 Refined Engine Studies

The selection of engines for refined studies was based on the screening evaluation conducted by P&WA and Boeing as well as by the other NASA SCAR airframe contractors. These refined studies consisted of further parametric cycle and installed evaluations of three engines selected from the initial Task VII and XIII parametric studies described in Section 3.1.

One engine selected for refinement was the VSCE-502 concept which showed significant system improvements compared to the best engines evaluated in the Phase I studies.

The second engine was the single rear-valve VCE concept. It was defined late in the Phase II study and evolved from the VSCE-502 concept and the dual-valve VCE concepts. It was selected because it had the potential for significant improvements relative to earlier valved engine concepts.

A third engine, the single front-valve VCE concept was also chosen for these refinement studies. The Phase II parametric study of single front-valve engine concepts (Section 3.1.3) identified one engine, the VCE-107M, as having cruise performance and inlet flow matching characteristics that were considerably better than the Phase I front-valve engine concepts. Although the parametric integration studies of the VCE-107M (Section 3.1.5) indicated it was not as attractive as the VSCE concept, it was felt that with refinement, the weight of this engine could be reduced, making it more attractive on an overall system basis.

3.2.1.1 Variable Stream Control Engine (VSCE)

The results from the parametric integration studies and the preliminary design studies led to a refined version of the VSCE concept, designated the VSCE-502B. In arriving at the VSCE-502B cycle, several component and cycle refinements were evaluated:

- The impact of increased supersonic cruise airflow,
- The sensitivity of engine performance to various amounts of variable fan geometry,
- The impact of variable turbine geometry on performance and inlet matching,
- The effect of component and cycle refinements.

These parametric cycle and integration studies of the VSCE concept led to the following refinements relative to the initial VSCE-502 data-pack engine.

- An increase in cycle pressure ratio to 20:1, which results in a maximum compressor exit temperature of 1300°F (700°C) at the Mn 2.4 cruise condition. This high cooling air temperature level will require advanced, high creep-strength disk materials for the back end of the high-pressure compressor as well as the high-pressure turbine.
- Increased fan rotor-stator axial spacing for improved aft radiated fan noise characteristics and a near-sonic inlet for controlling forward propagating fan noise.
- An increase in supersonic cruise inlet and engine airflow. This required an increase in inlet capture area with an attendant weight penalty.
- An increase in the maximum primary combustor temperature to 2800°F (1530°C) with a corresponding increase in turbine cooling airflow. In addition, the primary burner design was updated to reflect one of the experimental configurations being evaluated in the NASA/P&WA Experimental Clean Combustor Program (NAS3-16829). The configuration chosen was the swirl Vorbix design (Vorbix = Vortex burning and mixing).
- A refined duct-burner definition, for consistency with the low-emissions high-efficiency piloted Vorbix concept. This improved duct-burner resulted in improved supersonic cruise performance.

- An advanced technology branch diffuser concept for the duct-burner. This provides additional diffusion required for the high-efficiency duct-burner concept without an engine length penalty.

- Study of variable turbine geometry in the VSCE-502B engine did not provide significant improvement. At this point, it appears that any advantage that variable turbine geometry may offer can be accomplished by a change in engine cycle, thereby avoiding the complexity and attending penalties of variable turbines.

Table 3.2-I and Figure 3.2-1 illustrate how these cycle or component improvements affected the performance of the VSCE-502 engine. As shown, a 5.2% improvement in augmented TSFC has resulted from these refinements. This 5.2% improvement in TSFC is accomplished by a combination of refinements that include better supersonic airflow matching as well as improved duct-burner efficiency. Table 3.2-I shows that the increase in supersonic cruise airflow alone resulted in a 2.1% improvement in cruise performance.

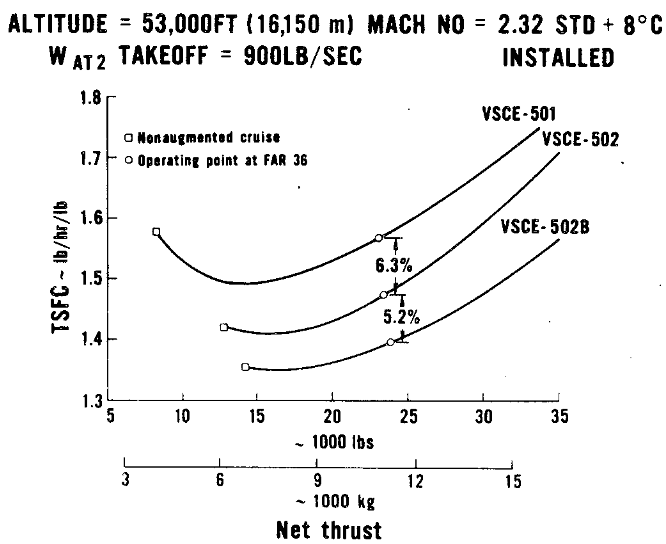


Figure 3.2-1 Estimated Supersonic Cruise Performance for VSCE Cycles

The TOGW improvements for the VSCE-502B are shown as a function of the airflow size parameter in Figure 3.2-2. The jet-noise characteristics of the VSCE-502B are the same as the original VSCE-502; therefore, the engine sizing discussion in Section 3.1.5 and the data of Figure 3.1-32 apply to the VSCE-502B as well. The VSCE-502B supersonic TSFC has improved significantly (5.2%) relative to the 502, which had improved by some 6.3% over the VSCE-501. The total improvement to TOGW for the 502B relative to the VSCE-501 is 13%. The TOGW comparison of these engines on the mixed mission is essentially the same as for the all supersonic mission.

TABLE 3.2-I

VSCE-502 CYCLE AND COMPONENT REFINEMENTS

Sea level static takeoff	Cycle characteristics: VSCE-502	Cycle characteristics: VSCE-502B	Cruise performance changes: Δ TSFC % subsonic cruise	Cruise performance changes: Δ TSFC % supersonic cruise
Corrected airflow				
W_{AT2} ~ lb/sec	900	→	0	0
(kg/sec)	(408)	→		
Bypass ratio	1.3	→	0	0
Fan pressure ratio	3.3	→	0	0
Cycle pressure ratio	15:1	20:1	-3.6	+1.0
Combustor temp				
Hot day takeoff ~ °F	2300	→		
(°C)	(1260)	→		
Hot day max climb ~ °F	2600	2800	+2.0	-1.3
(°C)	(1430)	(1540)		
Augmentor EFFICIENCY (Chemical)	90(97)	94.5(99.5)	+0.2	-1.3
Supersonic cruise airflow % of takeoff	68.5	74.5	0	-2.1
Other components	-	-	-2.0	-1.5
Engine + no. 33/rev weight ~ lbs	12,750	13,400	0	0
(kg)	(5780)	(6080)		
Total fuel consumption improvement =			-3.4 %	-5.2%

MACH NO. = 2.32 STD + 8°C UNSUPPRESSED ENGINES

*Based on coannular model test data and F_N/TOGW = 0.275

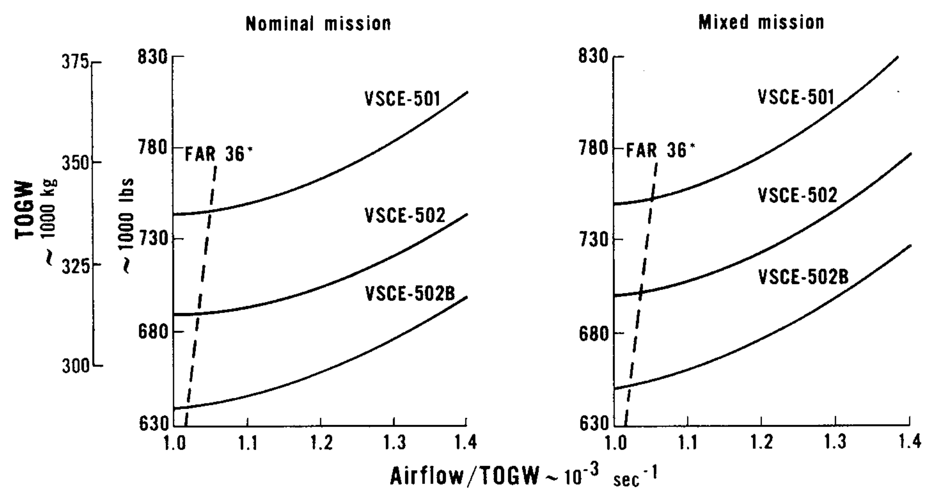


Figure 3.2-2 VSCE Take-Off Gross Weight Evaluation

The TOGW improvement from the VSCE-501 to the -502B is attributed primarily to the supersonic cruise TSFC improvements shown in Figure 3.2-1. Figure 3.2-3 shows the fuel burned vs. distance comparison for the VSCE-502 and -502B. The VSCE-502B has a slightly higher average supersonic climb rate than the -502 and reaches cruise altitude in less distance. This, combined with the better supersonic cruise range factor, results in the VSCE-502B's better overall performance.

3.2.1.2 Single-Rear-Value Variable Cycle Engine (VCE) Refinement Studies

The results of the initial parametric integration studies (Section 3.1.5) indicated that a competitive VCE concept must have the following characteristics:

- Turbojet performance at supersonic cruise
- Turbofan performance at subsonic cruise
- Good transonic thrust
- Turbofan weight characteristic
- Good supersonic climb and cruise inlet airflow match without compromises to inlet/engine/nozzle dimensions, complexity and weight.

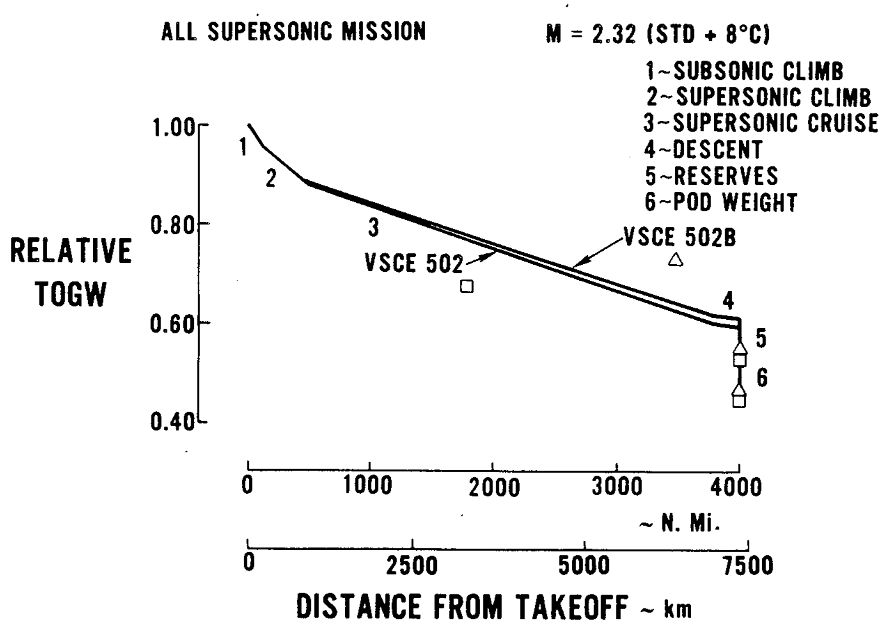


Figure 3.2-3 VSCE-502 and -502B Fuel Consumption Comparison

Due to both installation and performance compromises, the single-forward-valve and dual-valve VCE's evaluated in the initial parametric study did not meet the above criteria and consequently were not competitive with the VSCE. However a new valved engine design, the single-rear-valve VCE concept, shown schematically in Figure 3.2-4, generally meets these criteria and has the potential for significant improvements over the other valved engine configurations.

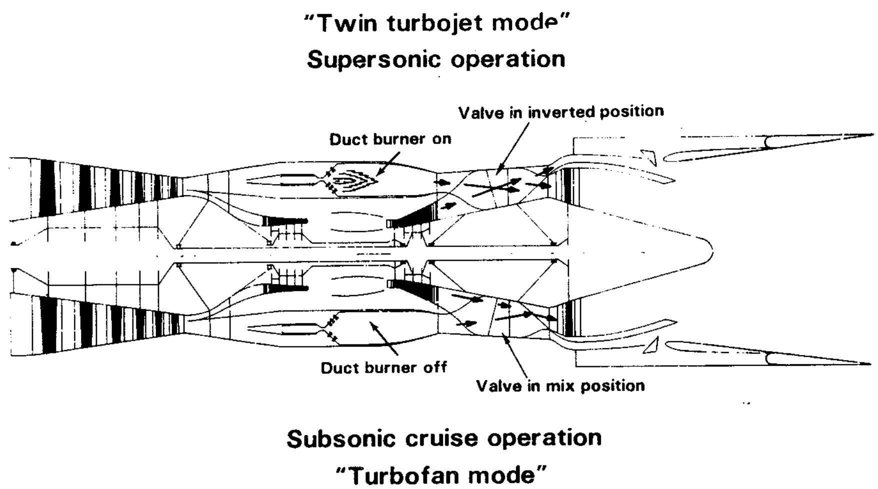


Figure 3.2-4 *Single Rear Valve Variable Cycle Engine*

The single-rear-valve VCE is a twin-spool configuration consisting of a multi-stage fan, high-pressure compressor, primary burner, high-pressure turbine, low-pressure turbine, duct-burner, flow inverter/mixer valve, an additional low-pressure turbine assembly located behind the valve, and a two stream nozzle. The nozzle has a fixed inner stream throat area, a variable outer stream throat area, and a free-floating nozzle exit area. Shown in the schematic are the two modes of operation for this VCE: the twin turbojet mode, which is achieved by using the valve to invert the two streams with the duct-burner turned on; and the turbofan mode, with the duct-burner turned off and the valve mixing the two streams prior to entering the rear low-pressure turbine.

This single rear-valve VCE concept has the following features:

- Twin turbojet cycle at supersonic cruise. This capability previously existed only in the heavier dual-valve VCE's.

- Total engine airflow is not affected by the valve position as was a problem with front-valve and dual-valve VCE's. Climb airflow and thrust are therefore not reduced when the engine is switched to the twin turbojet supersonic mode of operation.

- At take-off, the core stream can be throttled for intermediate jet velocities by operating in the low temperature (1900°F (1030°C) max. duct-burner temperature) twin turbojet mode. In addition, the primary burner can be controlled to achieve the proper jet noise balance between the two coannular streams. The duct-burner temperature is limited to 1900°F (1030°C) in order to minimize the cooling requirements for the flow inverter/mixer valve and the additional rear turbine.

- The rear-valve VCE concept may be capable of being adapted to benefit from the potential noise reduction associated with inverted velocity profiles for coannular nozzles.

- At subsonic conditions, in the turbofan mode, the high fan pressure ratio is effectively reduced by expansion through the rear turbine. This produces a lower fan pressure ratio cycle similar to the VSCE-502B which is more optimum for subsonic cruise operation.

- Locating the duct-burner ahead of the valve decreases engine length and improves the flow profile into the duct-burner relative to the dual-valve VCE's. This location does, however, require additional bleed air from the fan to cool the valve surfaces.

- The high BPR reduces the gas generator weight and helps to off-set the weight of the valve and additional turbine. This results in a total engine weight comparable to the VSCE concept.

- The duct-burner thrust efficiency is not penalized due to a parabolic temperature profile, because of the estimated attenuation of this profile through the rear turbine.

A preliminary assessment of the single-rear-valve VCE concept showed that it has good subsonic and supersonic cruise performance characteristics. Furthermore it is lighter than the previously studied valved engines. Based on these early encouraging results a limited parametric study was conducted.

The parametric study conducted concentrated on the effects of fan pressure ratio and duct-burner temperature variations. Table 3.2-II shows a summary of the parametric cycle characteristics. Comparisons of both subsonic and supersonic cruise performance levels indicated relatively small differences between the four engines. To facilitate the screening of these four engines, P&WA screened each cycle for the all supersonic mission only. Figure 3.2-5 shows that in terms of relative airplane TOGW, there exists only small differences in overall airplane performance. The VCE-112 and -113 have only slightly lower TOGW than the other two cycles. Since each of the VCE's studied could benefit from a higher second burner temperature, 1900°F (1030°C), this benefit was applied to the VCE-112 engine. Also, re-evaluation of the engine weight estimates indicated that there was a potential improvement to the VCE-112 weight when compared to the other engines. The TOGW reduction possible due to the reduction in engine weight and the increase in 2nd burner temperature is indicated in Figure 3.2-5.

TABLE 3.2-II

SINGLE REAR-VALVE PARAMETRIC STUDY ENGINE SUMMARY

Engine identification	VCE-110	VCE-111	VCE-112	VCE-113
Mission Mach no.	2.4	→	→	→
Airflow schedule	Boeing Mach 2.4 inlet	→	→	→
Cycle characteristics SLS takeoff				
Fan pressure ratio	4.8	5.3	5.8	4.8
Bypass ratio	2.5	→	→	→
Cycle pressure ratio	25:1	→	→	→
Combustor temperature, max				
Primary burner ~°F	2800	→	→	→
(°C)	(1540)			
Duct burner ~°F	1700	→	→	1900
(°C)	(930)			(1040)
Total corrected airflow ~ lb/sec	900			
(kg/sec)	(408)	→	→	→
Parametric engine weights and dimensions				
Bare engine weight (lbs)	base	+200	+400	0
Engine + N/R (lbs)	base	+250	+450	0

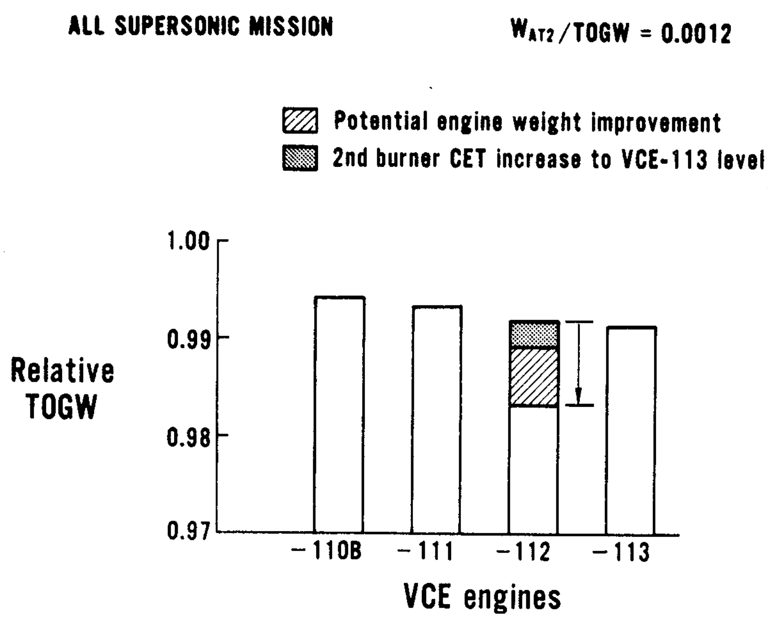


Figure 3.2-5 Single Rear Valve VCE Cycle Comparison

Both the P&WA and Boeing preliminary evaluations of the single-rear-valve VCE's indicated the VCE-112 cycle should receive further study. A data pack was therefore generated for the VCE-112B and released to NASA and associated SCAR airframe contractors. A comparision of this engine and the VSCE concept is presented in a following section.

3.2.1.3 Single Front-Valve VCE

During the parametric system and integration studies of the single front-valve VCE concept, two characteristics of this type of engine were identified as requiring further study. These were:

- During climb, the reduction in total engine airflow after the switch from the high to low bypass mode resulted in significant increases in inlet drag due to spillage effects. This compounded the effect of the reduced engine airflow on available thrust.

- When the valved engine was sized for the same take-off airflow as the VSCE (with the valved engine in the high bypass mode), the best single front-valve concept (VCE-107M) is approximately 25 percent heavier than the best VSCE concept (VSCE-502).

The large shift in inlet airflow when going from the high to the low bypass mode is an inherent characteristic of the single front-valve engine concept. By employing an auxiliary inlet for the second fan, the supersonic inlet can be sized for the airflow required by the first fan only. This reduces the inlet size and weight and improves the spillage or bypass loss characteristics during transonic and supersonic climb. This was one of the refinements evaluated for the front-valve concept. The other refinement involves a cycle change to reduce the number of fan stages and, in doing so, further lightens the engine. The VCE-107M parametric cycle had two fan assemblies, each requiring three stages to achieve a 2.5 FPR in the high bypass mode with acceptable surge margin. This conservative fan design was a result of the low spool rotational speed limitation set by the low-pressure turbine blade stress levels. By reducing the FPR from 2.5 to 2.0, the total number of fan stages was reduced from six to four. This change was accomplished while holding the maximum blade stress in the low-pressure turbine constant. This blade stress was a critical factor in this refinement study because even with advanced, high strength blade materials, it was the limiting parameter that set the fan rotational speed. Other adjustments in the other cycle characteristics were required to achieve acceptable take-off thrust and jet-noise levels without using suppressors. Table 3.2-III shows the resulting refined engine cycle, designated the VCE-108. The maximum combustor exit temperature was increased to 2800°F (1530°C) for consistency with the other refined engines. This table shows that as a result of the component and cycle changes incorporated in the VCE-108 cycle, a 10% reduction in engine weight was achieved. However, this improvement was accompanied by a loss in both subsonic and supersonic TSFC. For reference, the VSCE-502 is also listed in Table 3.2-III. Figures 3.2-6 and 3.2-7 compare the performance characteristics for subsonic (high bypass mode) and supersonic (low bypass mode) cruise. As shown in Figure 3.2-7, the supersonic TSFC (including inlet and nozzle drag) of all three engines is nearly equal at the typical cruise power setting. For subsonic cruise, the VCE-108 has nearly 7% higher TSFC compared to the VCE-107M.

TABLE 3.2-III

SINGLE FRONT-VALVE VCE REFINEMENT SUMMARY

HIGH BYPASS MODE

Engine identification	VCE - 107M	VCE - 108	VSCE - 502
Cycle characteristics (S.L.S. takeoff)			
Total corrected airflow W_{AT2} ~ lbs/sec (kg/sec)	900 (408) →		
Bypass ratio	1.5	1.6	1.3
Fan pressure ratio - 1	2.5	2.0	3.3
Fan pressure ratio - 2	2.5	2.0	—
Cycle pressure ratio	15.1 →		
Combustor exit temp.~°F Max climb (°C)	2600 (1430)	2800 (1540)	2600 (1430)
Engine weights			
Bare engine ~ lbs (kg)	Base	-1300 (-590)	-2700 (-1220)
Engine plus nozzle/reverser ~ lbs (kg)	Base	-1150 (-520)	-3100 (-1410)

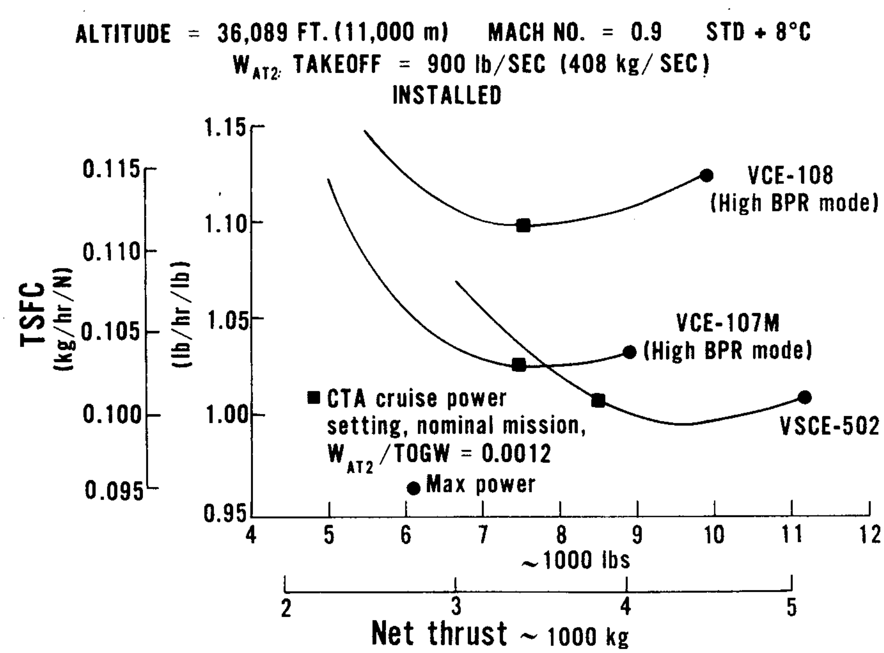


Figure 3.2-6 Estimated Subsonic Cruise Performance

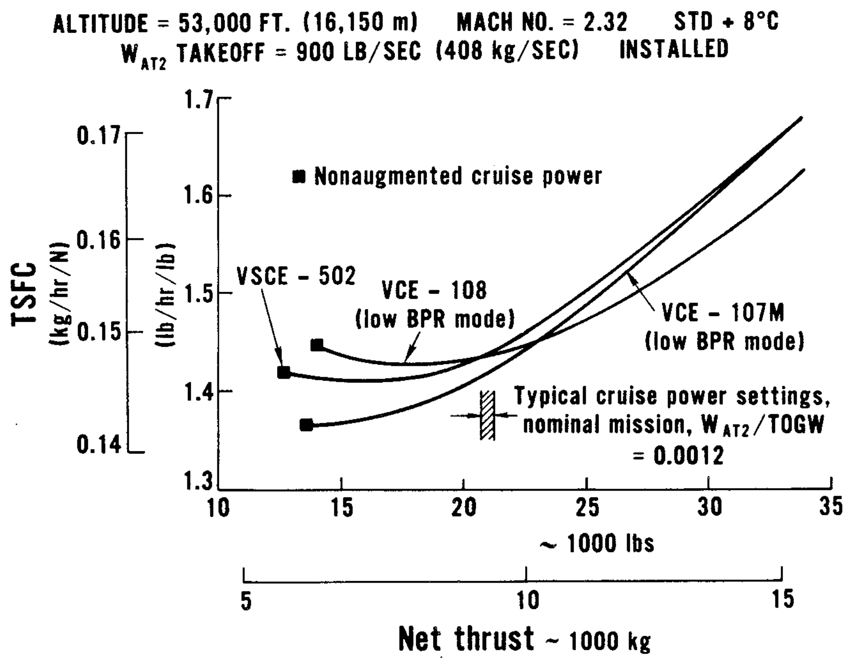


Figure 3.2-7 *Estimated Supersonic Cruise Performance*

To access the trade between reduced engine weight and the poorer engine performance, a system comparison of the VCE-108 cycle with the earlier VCE-107M and the VSCE-502 & -502B was made. This evaluation was optimistic for the VCE-108 in that it did not include any weight or dimensional penalty for the auxiliary inlet required by the second fan for the high bypass mode of operation. Figure 3.2-8 shows a comparison of the TOGW achieved with the VCE-108 as a function of the engine airflow loading parameter (WAT_2/TOGW). As shown by the figure, for the nominal (all supersonic cruise mission), the subsonic and supersonic cruise performance losses more than offset the 10% reduction in engine weight. For the mixed mission where subsonic cruise performance weighs more heavily, the VCE-108 fades even further because of its poorer subsonic TSFC.

Based on these system results, no further refinement of the single front-valve VCE was conducted. The refined VCE-108 was not released as a data-pack engine.

3.2.1.4 Refined Engine Comparison

The advanced component technology study results, outlined in Section 3.1.2, were utilized to define engine flowpaths for the refined VSCE-502B and the refined single-rear-valve VCE-112B. The engine flowpaths shown in Figures 3.2-9 and 3.2-10 established the component definitions and overall engine dimensions for engine weight estimates and for installation dimensions.

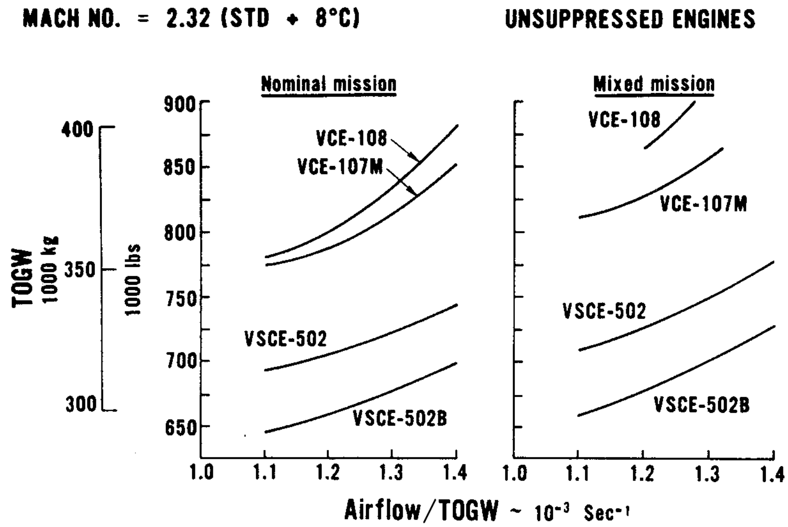


Figure 3.2-8 *Single Front Valve VCE TOGW Comparison*

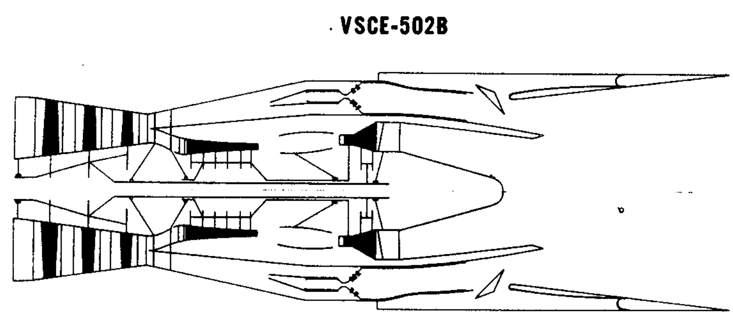


Figure 3.2-9 *Variable Stream Control Engine, VSCE-502B*

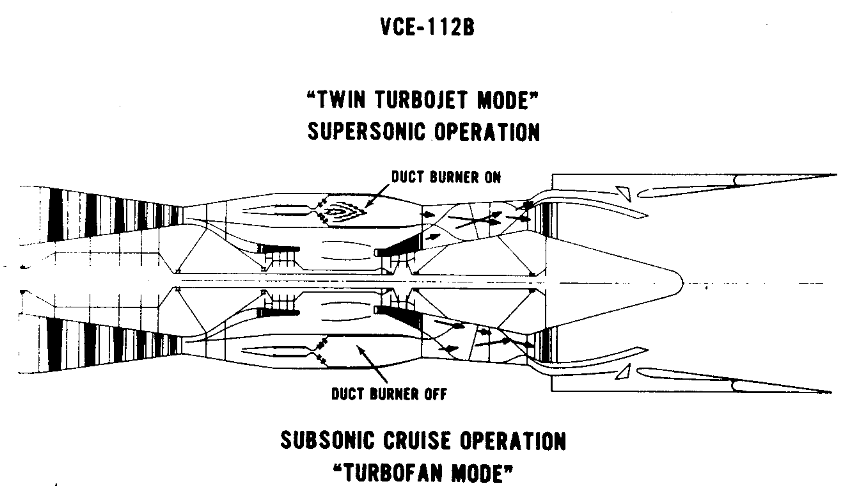


Figure 3.2-10 *Single Rear Valve Variable Cycle Engine, VCE-112B*

Table 3.2-IV summarizes the engine cycles, weights and dimensions for two data-pack parametric engines (LBE-405 & VSCE-502) and the refined engines VSCE-502B and VCE-112B. As shown by the table, the Task VII data-pack engines were designed with a maximum Mach number capability of 2.7. The refined engines (VSCE-502B and VCE-112B) have higher cycle pressure ratios which limit their application to a maximum cruise Mach number of 2.4. In addition, the refined engines have higher maximum primary combustor temperatures, 2800°F versus 2600°F (1530°C versus 1420°C).

TABLE 3.2-IV

REFINED ENGINE CYCLE AND INSTALLATION SUMMARY

		Task VII		Task XIII Refined Engines	
Engine Identification		LBE-405	VSCE-502	VSCE-502B	VCE-112B
Mission Mach No. Max.		2.7	2.7	2.4	2.4
Cycle Characteristics (S.L.S. Take-off)					
Fan Pressure Ratio		4.1	3.3	3.3	5.8
Bypass Ratio		0.1	1.3	1.3	2.5
Cycle Pressure Ratio		17:1	15:1	20:1	25:1
Combustor Temp. Max.					
Primary Burner	~°F)	2600	2600	2800	2800
	(°C)	(1430)	(1430)	(1540)	(1540)
Duct Burner	°F	-	-	-	1900
	(°C)				(1040)
Total Corrected Airflow					
	(lb/sec)	900	900	900	900
	(kg/sec)	(408)	(408)	(408)	(408)
Engine Weights and Dimensions					
Bare Engine Weight	~ lbs	13,000	9950	10,500	11,450
	(kg)	(5900)	(4510)	(4760)	(5190)
Engine + N/R	~ lbs	15,600	12,750	13,400	13,500
	(kg)	(7080)	(5780)	(6080)	(6120)
Max. Diameter	in.	85	89	88	82
	(m)	(2.16)	(2.26)	(2.24)	(2.10)
Engine + N/R Length	~ in.	301	253	266	305
	(m)	(7.65)	(6.43)	(6.76)	(7.75)

Engines weights shown in Table 3.2-IV include a variable primary stream nozzle for both Task VII data-pack engines and for the VSCE-502B. The VCE-112B engine weight assumes a fixed primary stream nozzle and a variable bypass stream nozzle. The VCE-112B requires a very optimistic duct-burner diffuser length. This is a result of letting the primary gas generator length set the overall engine length and not adding extra length required by a more conventional diffuser. Another assumption which kept the VCE-112B length to a minimum was that no increase in fan rotor-stator axial spacing was made. An increase was allowed for in the VSCE-502B. It was felt that the VCE-112B engine would not require the additional spacing since aft turbo-machinery noise would be dominant rather than fan noise, due to the addition of the large rear turbine assembly.

Figures 3.2-11 and 3.2-12 compare the supersonic and subsonic installed engine performance of the four engines shown in Table 3.2-IV. The installed performance shown includes:

- Inlet pressure recovery
- Aircraft bleed and housepower extraction
- Drags associated with inlet spillage, bypass, and boundary layer bleed (based on the Boeing Mn2.4 axisymmetric inlet)
- Nozzle internal performance
- Nozzle boattail drag

The LBE-405 engine allows for a penalty in the internal nozzle performance because of the difficulty in packaging the multi-tube suppressor together with a thrust reverser. It should be noted that, as with the VSCE-502B engine, refinements to the LBE-405 engine could improve subsonic and supersonic cruise performance. Because of the program scheduling restrictions, these improvements could not be made. However they are not expected to approach the levels realized in the VSCE engine.

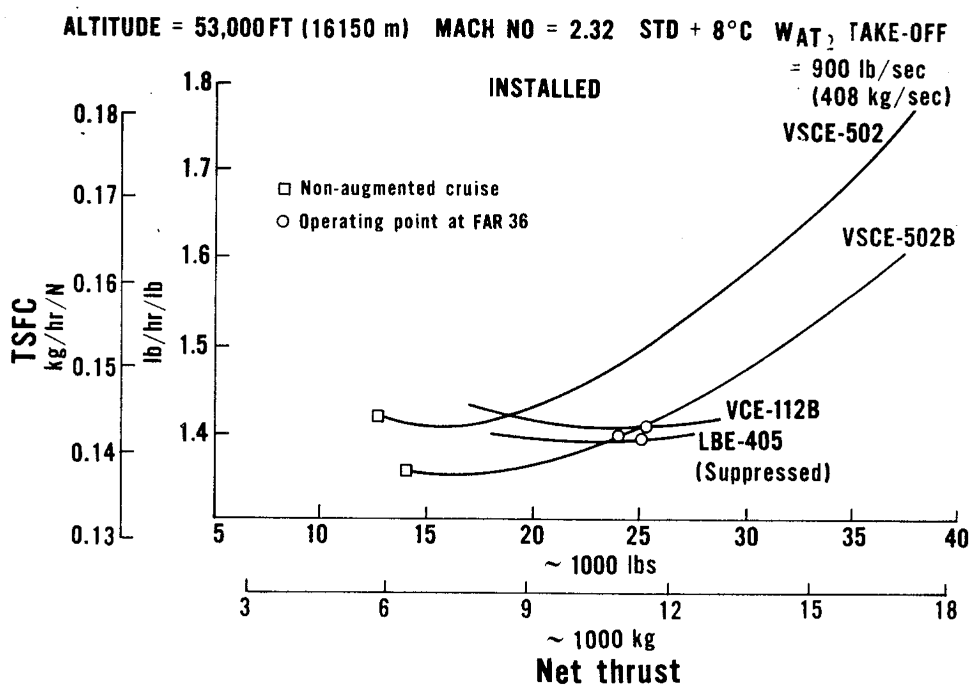


Figure 3.2-11 Estimated Supersonic Cruise Performance

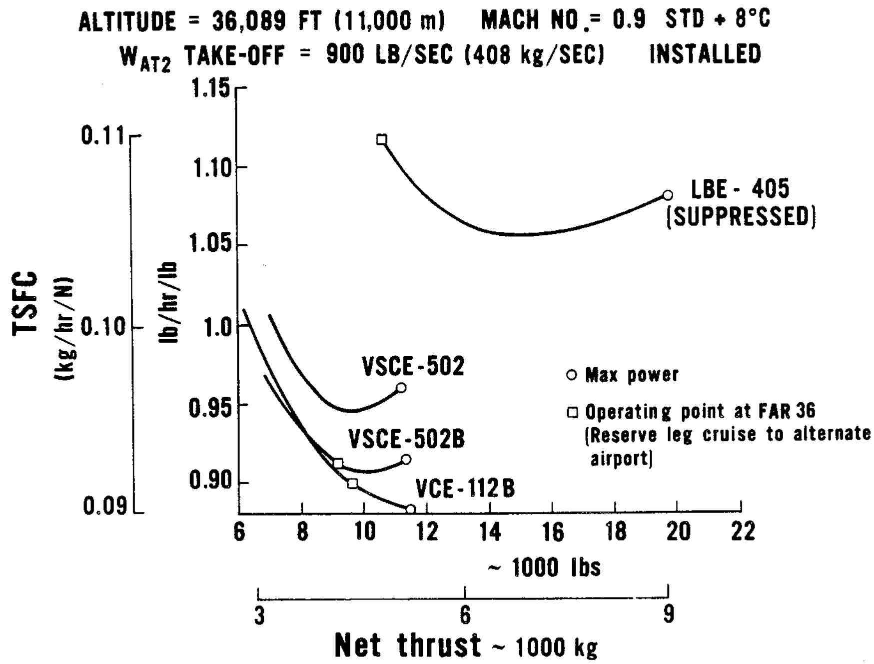


Figure 3.2-12 Estimated Subsonic Cruise Performance

3.2.2 System Evaluation of Refined Engines

3.2.2.1 P&WA System Evaluation of Refined Engines

The TOGW versus noise relationships for the best of each type of engine is shown in Figure 3.2-13. The results shown are for an all supersonic mission with engines sized for a take-off thrust loading (FN/TOGW) of 0.275. The VSCE-502 and LBE-405 were included to show improvement in the VSCE-502B and VCE-112B relative to these earlier data-pack engines.

The VSCE-502B has the lowest TOGW for any noise level of interest. The VCE-112B is slightly higher. This figure shows that compared to the earlier front and dual-value VCE's, the single-rear-valve VCE-112B is by far the best of the valued cycles and in fact is the only valved cycle studied to date that is competitive with the VSCE.

The family of curves shown as solid lines on Figure 3.2-13 represent engines with the sideline jet noise level estimated using the SAE prediction method. The dashed curves assume coannular nozzle noise benefit or, in the case of the LBE-405, assume an advanced multi-tube suppressor. In either case, the VSCE-502B is the best engine. The front and dual-valve VCE's are not competitive even with the coannular noise benefit. For the mixed mission, the relationship between the VSCE-502B and VCE-112B remains essentially unchanged, while the LBE-405 is significantly worse because of its poor subsonic TSFC.

All supersonic mission F_N/TOGW = 0.275

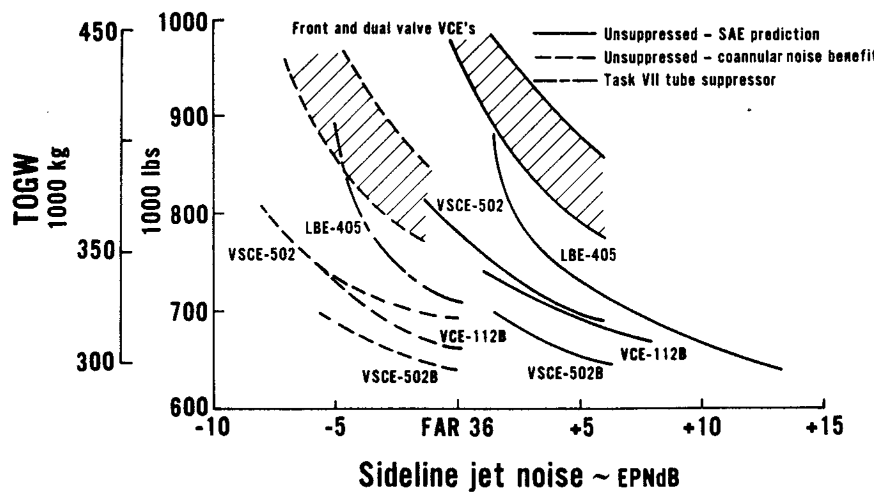


Figure 3.2-13   Summary Engine Comparison

A summary of some key airplane/engine system parameters is presented in Table 3.2-V. The VSCE-502B and VCE-112B engines are sized for jet-noise levels that meet FAR36, assuming the full coannular static test benefit, while the LBE-405 is sized for FAR36 assuming the multi-tube suppressor characteristics shown in Figure 3.1-7. The VSCE-502B has the lowest TOGW and the lowest block fuel per passenger mile of any of the engines. The supersonic cruise range factors (R.F.) are very close for all three engines while the subsonic cruise range factor for the LBE-405 is significantly worse than the other engines.

3.2.2.2 Boeing Integration Evaluation of Refined Engines

One of the recommendations from the initial Boeing parametric integration evaluations of the data-pack engines was to refine the cycles by examining higher airflow schedules; improved duct-burner efficiency; front frame diameter of the VSCE, changes in bypass ratio, fan pressure ratio and combustor exit temperature of the duct-burner; and configuration improvements for the valved engine concepts. These refinements were accomplished in an extension of the original contract and resulted in definition of refined cycles designated VSCE-502B and VCE-112B. The evaluation of these cycles, combined with improvement in airframe drag characteristics associated with a blended wing airplane design, shows nearly equal performance of the two cycles for a total range improvement of some 1000 N.MI (1850 km) over the baseline conventional engine from Phase I (D/H TF C-D).

TABLE 3.2-V

SUMMARY OF KEY AIRPLANE/ENGINE SYSTEM PARAMETERS, ALL SUPERSONIC MISSION, FAR 36 SIDELINE NOISE

	VSCE-502B		VCE-112B		LBE-405	
	Value	Δ%	Value	Δ%	Value	Δ%
Design Mission						
TOGW ~lb	640,000	0	662,000	+3.4	710,000	+10.9
(kg)	(290,300)		(300,300)		(322,000)	
WAT_2/TOGW ~sec^{-1}	1.020	0	1.025	+0.5	1.045	+2.5
Supersonic Cruise						
TSFC ~lb/hr/lb	1.403	0	1.413	+0.7	1.401	-0.1
(kg/hr/N)	(0.143)		(0.144)		(0.142)	
L/D	9.52	0	9.62	+1.0	9.64	+1.3
R.F. ~N.Mi	9315	0	9344	+0.3	9451	+1.4
(km)	(17250)		(17300)		(17500)	
Subsonic Cruise*						
TSFC ~lb/hr/lb	0.961	0	0.950	-1.1	1.166	+21.3
(kg/hr/N)						
L/D	14.25	0	14.17	-0.6	13.82	-3.0
R.F. ~N.Mi	7884	0	7932	+0.6	6304	−20
(km)	(14600)		(14690)		(11675)	
Fuel/TOGW	0.4517	0	0.4581	+1.4	0.4604	+1.9
Mission	0.3851	0	0.3896	+1.2	0.3811	-1.0
Reserve	0.0666	0	0.0685	+2.8	0.0793	+19.1
Pod/TOGW	0.0848	0	0.0874	+3.1	0.1025	+20.9
(Pod and Fuel)/TOGW	0.5365	0	0.5455	+1.7	0.5629	+4.9
Average Mission						
lb Fuel/Pass/N.Mi	0.200	0	0.210	+5.0	0.237	+18.5
(kg Fuel/Pass/km)	(0.049)		(0.051)		(0.058)	

*Reserve cruise to alternate airport

At the end of the parametric integration work described in Section 3.1, the VSCE-502 and a preliminary version of the single rear-valve VCE had been defined, evaluated and identified as the most promising concepts. The evaluations indicated the potential for additional range improvement through refinement of cycle characteristics to optimize the engine/airframe combination. It was also evident that further reductions in required thrust, and thus engine size, could be achieved by identified modifications to the airplane to reduce transonic and supersonic drag levels. The opportunity to combine the airplane improvements and these engine cycle refinements was provided by a NASA Langley Contract (NAS1-13559), "Advanced Supersonic Configurations Studies Using Multi-Cycle Engines for Civil Aircraft," and an extension to Task XIII of the NASA Lewis/Pratt & Whitney Aircraft Contract (NAS3-16948), "Advanced Supersonic Technology Propulsion Study." Under the Langley contract, the airframe was modified and the engines re-matched with a resultant improvement in the transonic/supersonic operating L/D's of approximately 20% (relative to the 1971 SST configuration). Under the NASA Lewis/P&WA Task XIII extension, cycle refinements in terms of bypass ratio, fan pressure ratio, combustor exit temperature, supersonic airflow and front frame geometry were optimized to match the blended wing/body airframe. The refined VSCE-502B and VCE-112B cycles were integrated with the airframe and the range performance characteristics were calculated.

Evaluation of Selected Variable Cycle Engines

The installed performance characteristics for the refined VCE-112B and the VSCE-502B engines are shown in Figure 3.2-14. The data are shown for 900 pps (408 kg/sec) versions of the engines. The installed performance includes the intake excess air drags and the boattail drags effects at off-design operation.

The VSCE-502B climb performance is shown for a power setting (P.C. 12) which was found to be near optimum for the earlier VCE-502 data-pack engine as installed in the non-blended delta configuration. For the blended delta configuration, a slightly lower power setting would be optimum.

A scaled nacelle drawing was prepared for each engine installation (Figures 3.2-15 and 3.2-16). The pods were integrated with the wing at both the inboard and outboard locations. These drawings were used for pod drag and weight estimates.

In the course of defining the VCE-112B installation, it was found that the nozzle exit area was under-expanded, and that an excessive boattail angle would result. P&WA then provided a geometry and weight adjustment increment, +170 lb (77 kg), for the fully expanded cruise nozzle, which is shown in the installation drawing and included in the weight.

Nacelle radius distributions for the VSCE-502B and VCE-112B evaluations are shown in Figure 3.2-17 with installed drags shown on Figure 3.2-18. The pod Weight scaling data is shown on Figure 3.2-19.

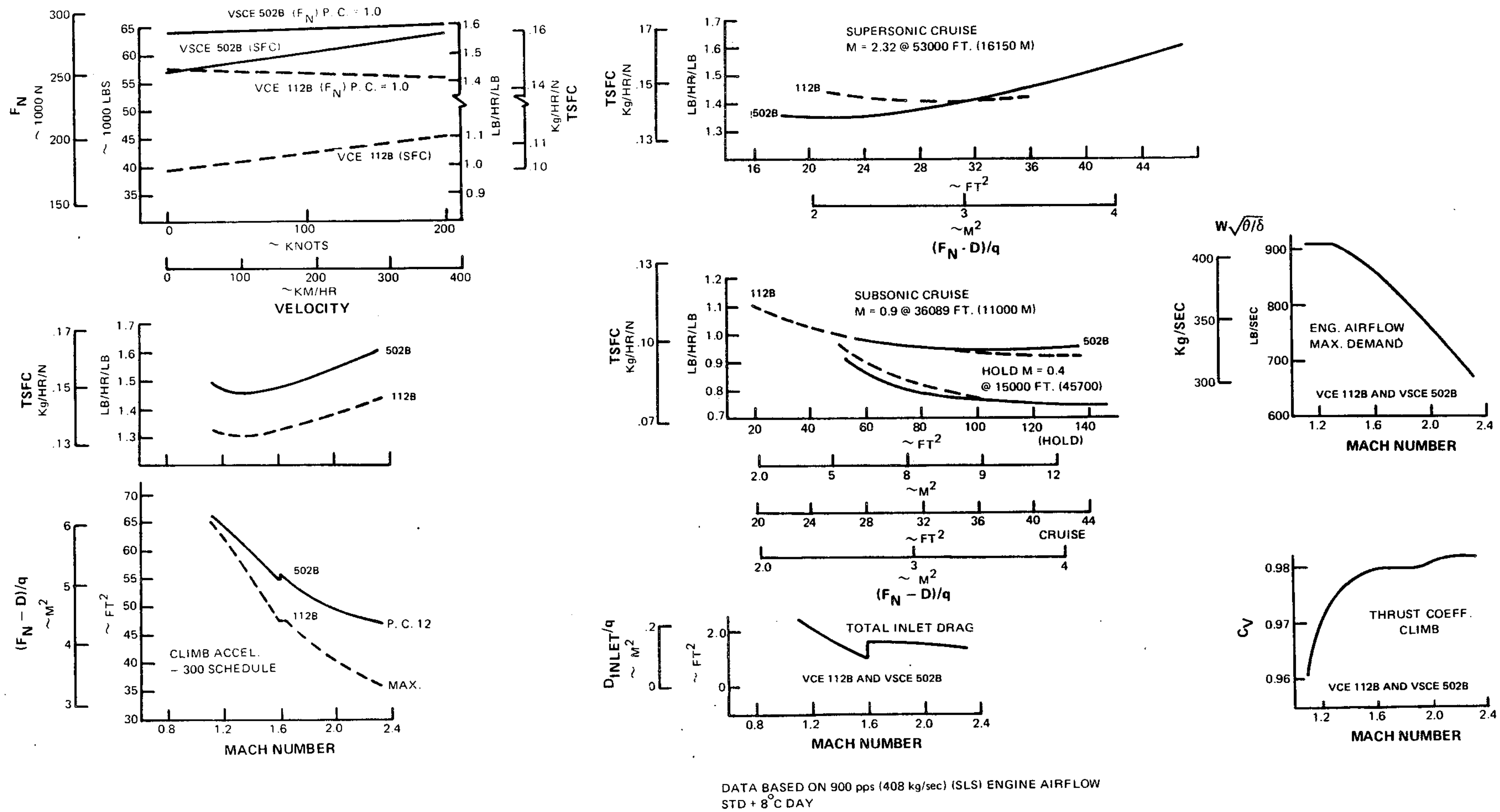


Figure 3.2-14 Installed Engine Performance Summary, VSCE-502B and VCE-112B

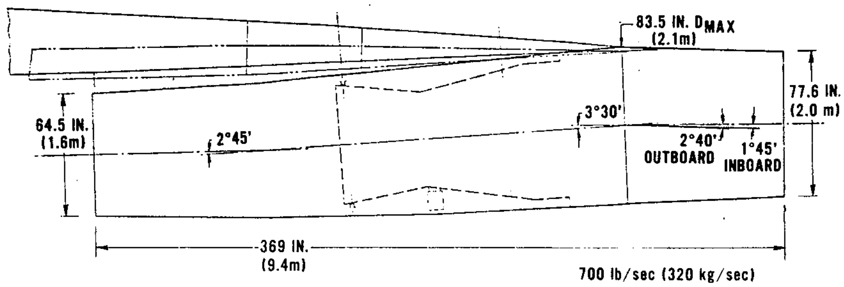


Figure 3.2-15 VSCE-502B Pod

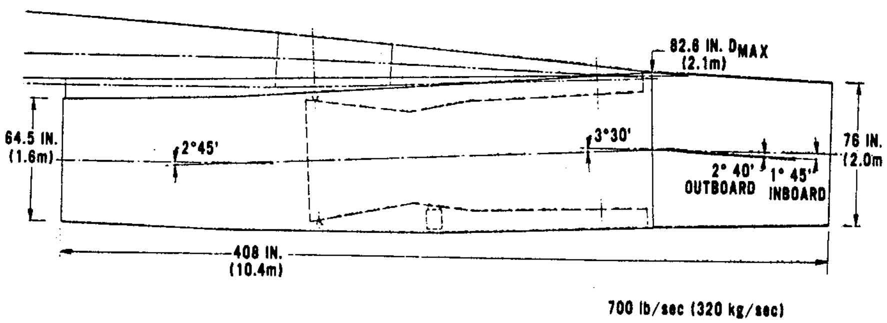


Figure 3.2-16 VCE-112B Pod

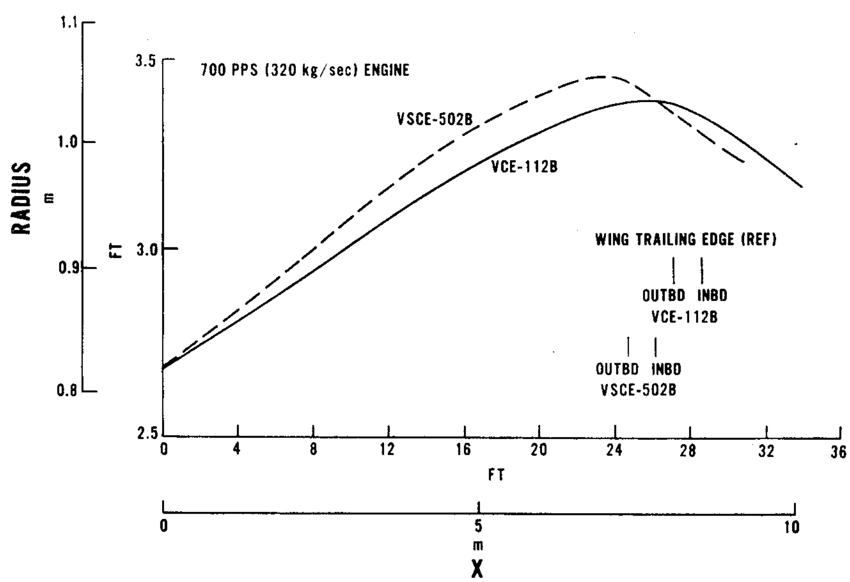


Figure 3.2-17 VSCE-502B and VCE-112B Nacelle Geometry

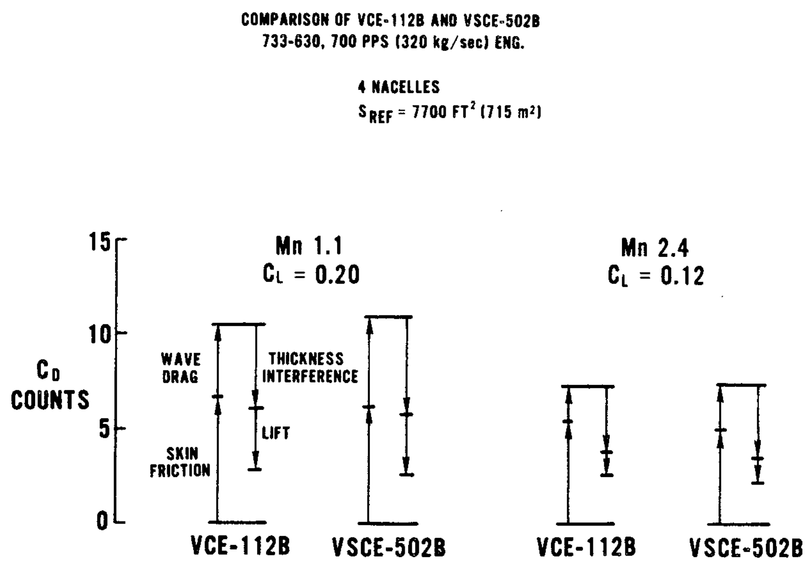


Figure 3.2-18 Nacelle Drag Summary Comparison of VCE-112B and VSCE-502B

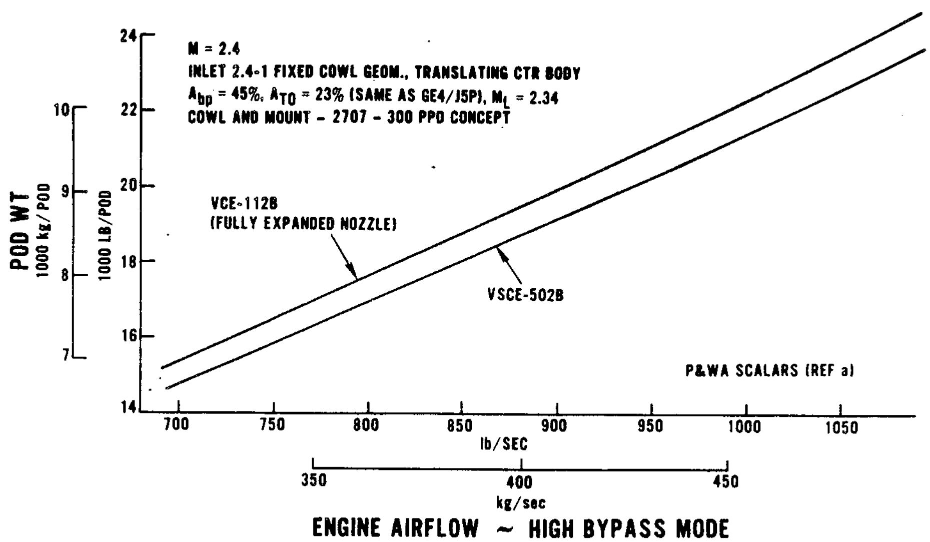


Figure 3.2-19 Pod Weight Data for VSCE-502B and VCE-112B

Detailed mission performance analyses were conducted on the two propulsion systems in order to assess the engine/airframe matching characteristics. The analysis was based on a blended delta configuration. Engine size was parametrically varied to determine the airflow for optimum range while achieving a minimum transonic climb thrust margin of 0.3, a time to climb to cruise altitude no greater than 0.75 hours, and a ratio of subsonic to supersonic cruise range factor equal to/or greater than one. The lift-off thrust required to meet the Boeing take-off field length criterion of 12000 feet (3660 m) on a standard + 10°C day, has been estimated to be 44,500 lb (19.9×10^4N) per engine. This level of thrust could be provided at all engine sizes considered. These analyses did not address the noise aspects of engine/airplane matching in any detail, due to the lack of definitive noise characteristics data for dual-stream engines.

Figure 3.2-20 shows that the VCE-112B engine size for maximum range is approximately 650 lb/sec (290 kg/sec). At this engine size the transonic thrust margin is 0.30 which meets the objective. Figure 3.2-21 shows that the optimum subsonic/supersonic cruise match (equal cruise range factors) occurs at a VCE-112B engine size of 650 lb/sec (290 kg/sec), but the time to climb is 0.25 hours more than the goal of 0.75 hours. Increasing the engine size to meet the time to climb objective (airflow = 700 lb/sec (310 kg/sec)) would result in a 20-25 n.mi. (37-46 km) range penalty. In addition, the cruise match worsens slightly such that the airplane would suffer a 0.8% reduction in range flying subsonically. Conversely, the transonic thrust margin would increase from 0.3 to 0.39.

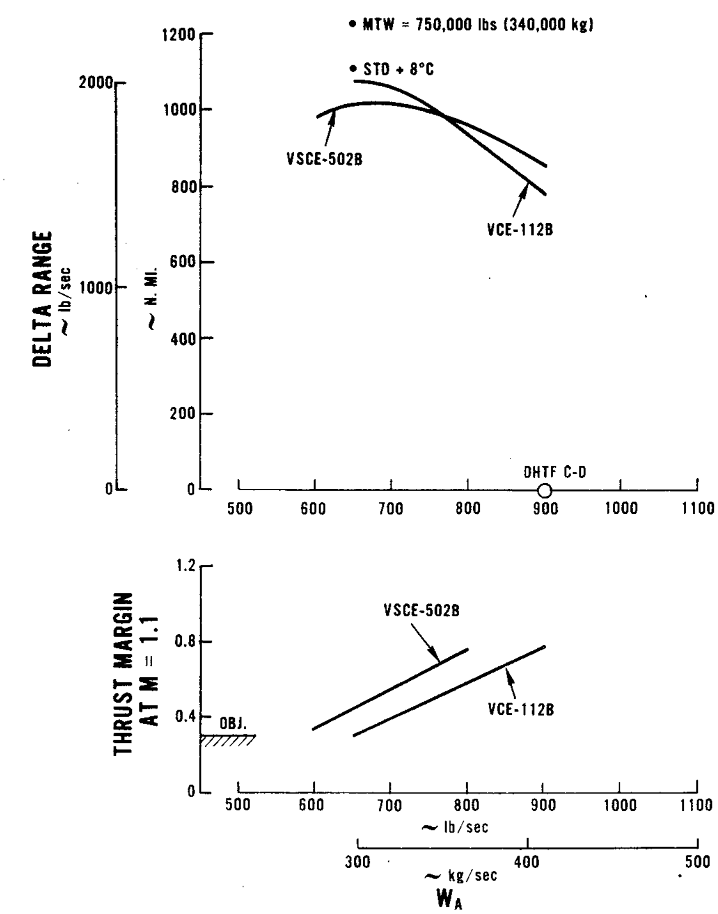


Figure 3.2-20 *Effect of Engine Size on Range and Transonic Thrust Margin for VSCE-502B and VCE-112B, MN = 1.1*

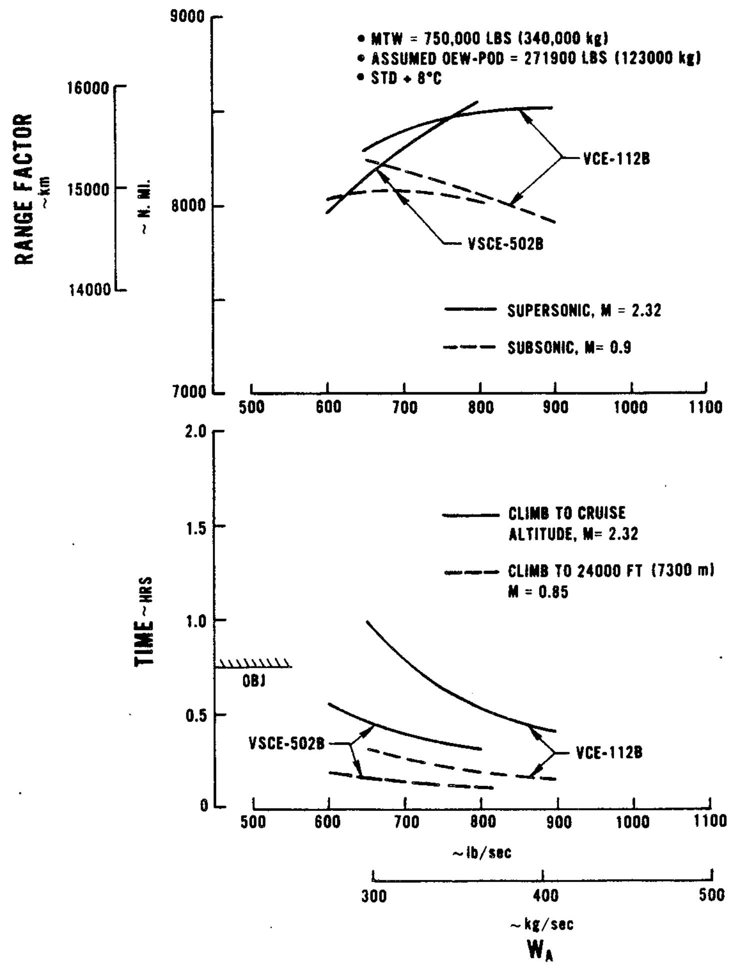


Figure 3.2-21 *Cruise Match and Time to Climb Comparison for VSCE-502B and VCE-112B*

Maximum range for the VSCE-502B is obtained with a 700 lb/sec (310 kg/sec) airflow as shown in Figure 3.2-20 and is 55 miles (100 km) less than the maximum range of the VCE-112B. The transonic thrust margin at this engine size is 0.544, considerably larger than the objective of 0.3. Figure 3.2-21 shows that at a VSCE-502B engine size of 700 lb/sec (310 kg/sec) the subsonic cruise range factor is approximately 2.3% lower than the supersonic cruise range factor (the best match is at 625 lb/sec (280 kg/sec)). Time to climb to cruise altitude for a 700 lb/sec (310 kg/sec) engine size is 0.4 hours. Decreasing the VSCE-502B engine size to 650 lb/sec (290 kg/sec) would reduce the range by less than 5 nautical miles (9 km) and improve the subsonic/supersonic cruise match by approximately 1.4% while the transonic thrust margin would decrease to 0.438 and time to climb would increase to 0.46 hours. Since the transonic thrust margin and time to climb to cruise altitude far exceed the objectives, an optimization of the climb power settings could lead to an increase in range for the VSCE-502B.

The results of this study indicate that both of these refined engines, the VCE-112B and the VSCE-502B, achieve satisfactory engine airframe matching characteristics at engine size of 700 (310) and 650 lb/sec (290 kg/sec), respectively, when applied to the blended delta configuration.

3.2.3 Noise Estimates

Throughout the Phase II parametric cycle and integration studies summarized in Section 3.1, jet noise was a basic consideration in comparing and evaluating candidate engines. For each type of engine concept, a range of cycle parameters was evaluated. Installed engine performance and weight estimates were factored into an overall system assessment, expressed in terms of gross airplane weight versus sideline jet noise. Figure 3.1-15 is a typical curve showing the results of these TOGW versus noise studies. On the basis of these noise-system assessments, the best cycle was selected to represent each type of conventional and unique engine concept. More extensive noise estimates were then made for the selected representative engines. This section summarizes these more detailed noise calculations. As described in Section 2.2.4, the procedure used to estimate these noise levels is based on the proposed revision to the SAE AIR 876 jet noise prediction method with relative velocity accounting for flight conditions.

The four engines that were analyzed more extensively for noise characteristics were the Low Bypass Engine (LBE), the Variable Stream Control Engine (VSCE), the single front-valve Variable Cycle Engine (VCE-107M) and the dual-valve Variable Cycle Engine (VCE-201B). The single rear-valve VCE concept was not included in this more detailed noise evaluation because it evolved from these data-pack engines and was defined late in the Phase II study. The Phase III study will include a noise evaluation of this rear-valve VCE concept.

All of the noise estimates reviewed in this section are based on engines with low-noise, near-sonic inlets which were assumed to reduce engine inlet noise by 20 EPNdB. Two levels of acoustic treatment were evaluated for each engine. The first level is obtained by applying acoustic treatment to the duct behind the fan which also serves as the diffuser between the fan and the duct-burner. The second level is obtained by a more extensive level of acoustic treatment, assuming the duct-burner liner can serve the dual function of a thermal shield plus acoustical noise attenuation. These two levels were evaluated in order to determine the sensitivity of overall engine noise to different levels of acoustic treatment for each engine configuration. The level of acoustic treatment is expressed in terms of treated duct length to passage height ratios (L/H). The corresponding fan noise reductions in terms of Δ EPNdB are also shown in Table 3.2-VI. These L/H values are based on treatment for the inner and outer duct walls only: none of the engines evaluated had acoustically treated splitter rings in the fan duct. Because of the small duct height for the LBE, the 2nd level of acoustic treatment was not evaluated. Weight and pressure loss penalties associated with acoustic treatment were not included in this evaluation.

TABLE 3.2-VI

LEVELS OF ACOUSTIC TREATMENT FOR REPRESENTATIVE ENGINES

Engine	Level of Acoustic Treatment [1]		L/H [2]	ΔEPNdB From Acoustic Treatment
LBE	1		36	15.5
VSCE	1		7	12.5
	2		12	13.5
Single Front-Valve VCE-107M	1	Front Duct	14	13.5
		Rear Duct	7	
	2	Front Duct	20	14.5
		Rear Duct	13	
Dual-Valve VCE-201B	1	Front Duct	5	12.5
		Rear Duct	14	
	2	Front Duct	15	15.5
		Rear Duct	25	

(1) Level 1 is based on acoustic treatment along the inner and outer walls of the duct between the fan and duct-burner.

Level 2 assumes the duct-burner liner can also serve as acoustic treatment.

(2) L/H is the ratio of treated duct length to duct height.

3.2.3.1 Results

Noise levels were estimated first for each of these four engine types without jet noise suppressors and without the coannular nozzle noise benefit. Each type of engine was throttled to reduce the jet noise in order to meet FAR 36 (108 EPNdB) at the sideline measuring station. The engine was then sized to meet the study groundrule of a nominal 4000 nautical mile (7400 km) range with a 292 passenger payload. TOGW was the variable determined for each type of engine. Table 3.2-VII summarizes the noise-related engine conditions at the three noise measuring stations defined in FAR 36: sideline, community with cut-back power, and approach. The climb-path for the community noise estimates is defined in Figure 3.2-22. Engine size in terms of total airflow and TOGW levels are also listed in Table 3.2-VII. The TOGW levels in Table 3.2-VII and in the following tables are based on a takeoff thrust loading ratio of 0.275 (engine thrust/TOGW at rotation). The LBE was designed for a mixed-flow nozzle. The other three engines have separate nozzles for the bypass stream and the engine stream. These conditions and the resulting noise estimates for the valved VCE's are based on these valved engines operating in the low-noise mode (high BPR low FPR). Results for these unsuppressed engines are summarized in Table 3.2-VIII. 90 EPNdB noise contours were also estimated for each of these engines. The results are shown in Figure 3.2-23. Conclusions from these noise estimates are discussed below.

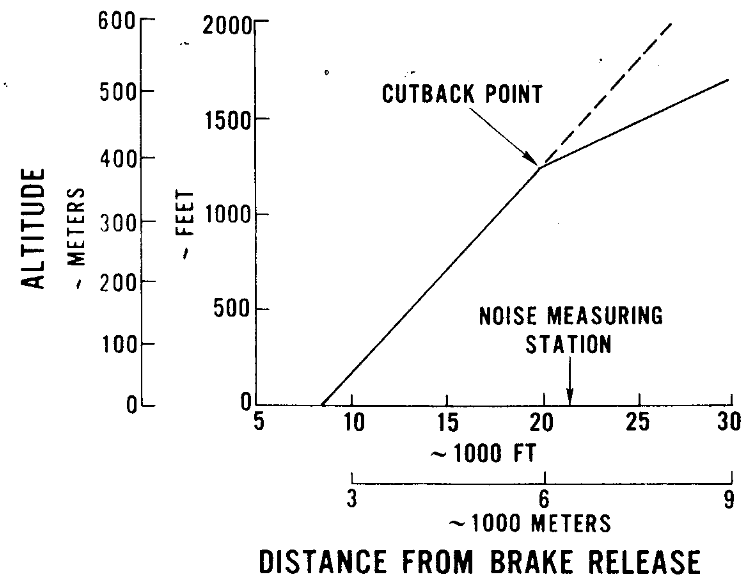


Figure 3.2-22 Climb Path for Noise Contour Analysis

TABLE 3.2-VII

NOISE-RELATED ENGINE OPERATING CONDITIONS FOR UNSUPPRESSED NOISE ESTIMATES

Engine Type	LBE			VSCE			Single Front-Valve VCE-107M			Dual-Valve VCE-201B		
Station	Sideline	Community	Approach	Sideline	Community	Approach	Sideline	Community	Approach	Sideline	Community	Aprpoach
Total Engine Airflow ~lbs/sec (kg/sec)	1,170 (530)	–	–	1,100 (500)	–	–	1,340 (620)	–	–	2,000 (910)	–	–
TOGW ~lbs (kg)	800,000 (360,000)	–	–	760,000 (345,000)	–	–	900,000 (410,000)	–	–	1,200,000 (540,000)	–	–
Jet Velocities ~ft/sec (m/sec)												
Fan 1	–	–	–	1,290 (390)	1,100 (340)	430 (132)	1,560 (475)	990 (300)	710 (217)	1,390 (425)	1,030 (315)	690 (210)
Fan 2	–	–	–	–	–	–	–	–	–	1,500 (460)	980 (300)	670 (205)
Engine	1,510 (460)	1,200 (365)	670 (205)	1,600 (490)	1,120 (340)	900 (275)	1,330 (405)	1,300 (400)	360 (110)	1,390 (425)	1,200 (365)	320 (98)
Jet Temperatures ~°F (°C)												
Fan 1	–	–	–	330 (166)	320 (160)	230 (110)	1,210 (650)	360 (182)	200 (93)	740 (393)	270 (132)	180 (82)
Fan 2	–	–	–	–	–	–	–	–	–	940 (490)	270 (132)	170 (77)
Engine	880 (470)	710 (375)	490 (254)	1,240 (670)	1,240 (670)	790 (420)	1,090 (590)	1,090 (590)	740 (393)	1,360 (740)	1,320 (725)	960 (515)

TABLE 3.2-VIII

EPNdB NOISE ESTIMATES FOR REPRESENTATIVE AST ENGINES WITHOUT JET NOISE SUPPRESSORS(1)

Engine	Noise Station / Level of Acoustic Treatment(2)	Sideline 1	Sideline 2	Community With Cut-Back 1	Community With Cut-Back 2	Approach 1	Approach 2	Traded Noise Including/Excluding Approach 1	Traded Noise Including/Excluding Approach 2
LBE	Jet	107.5	–	105.0	–	91.0	–		
	Fan	88.5	–	98.0	–	108.0	–	109/108	–
	Total	108.5	–	107.5	–	110.5	–		
VSCE	Jet	107.0	107.0	103.5	103.5	100.0	100.0		
	Fan	94.5	93.5	103.5	102.5	112.0	111.0	113/109	112/109
	Total	108.5	108.5	109.5	109.0	115.0	114.0		
Single Front Valve	Jet	106.5	106.5	105.5	105.5	91.0	91.0		
VCE-107M	Fan	94.5	93.5	104.0	103.0	111.0	110.0	111/109.5	111/109
	Total	108.0	107.5	111.0	110.0	113.0	112.5		
Dual Valve	Jet	106.5	106.5	103.0	103.0	93.0	93.0		
VCE-201B	Fan	95.0	92.0	105.0	102.0	110.0	107.0	111/109	109/108
	Total	108.0	107.5	110.0	108.0	112.5	110.0		

(1) Noise estimates are for four engines and allow for fuselage shielding and ground attenuation effects.

(2) Assuming low noise, near-sonic inlets and acoustically treated ducts as described in Table 3.2-VI.

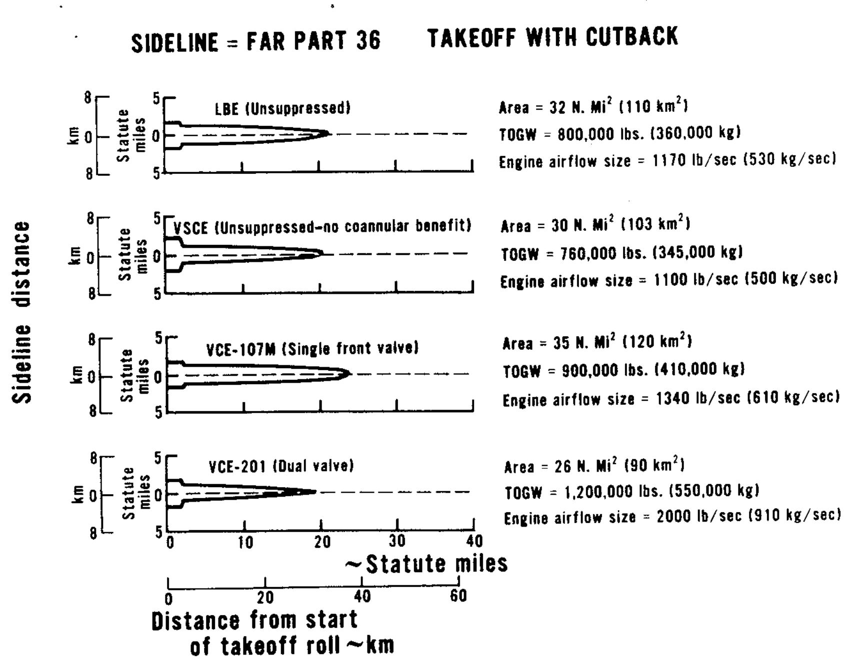


Figure 3.2-23 Comparison of 90 EPNdB Noise Contours

Additional noise estimates were then calculated to determine the effect of jet noise suppressors and also to assess the coannular noise benefit described in Section 4.1. Two types of jet noise suppressors were evaluated: multi-tube suppressors for the mixed-flow LBE and a finger suppressor applied only to the bypass stream of the VSCE. The jet noise reductions assumed for these suppressors are shown in Figure 3.1-7. The coannular noise benefit assumed for these noise calculations is consistent with the static experimental data obtained in the NASA/P&WA test program. These experimental data include the effect of acoustic treatment in the ejector region of these nozzle systems. The valved VCE's were not evaluated with suppressors because it was felt that they would become more complicated and less attractive if they were to bear the performance and weight penalties associated with suppressors, especially when these suppressors would have to be applied to two bypass streams. Evaluation of the coannular nozzle noise benefit for the most promising valved Variable Cycle Engine – the single rear-valve concept – is planned in the following Phase III propulsion system studies.

Table 3.2-IX lists the engine operating conditions that were evaluated for the LBE and VSCE engines with jet noise suppressors. In general, each engine was throttled so that with either a jet noise suppressor or with the coannular nozzle noise benefit, the sideline jet-noise level would meet FAR 36. Each engine was then sized to meet the range and payload groundrules. As indicated in Table 3.2-IX, the engine sizes, in terms of air flow rate, were much smaller than those in Table 3.2-VII where the FAR 36 sideline noise level was met without suppressors and without the coannular noise benefit. Two power settings were evaluated for each engine concept. For the VSCE, the first column in Table 3.2-IX corresponds to a take-off condition with the fan operating at its design pressure ratio (3.3:1). The second column is for a reduced fan pressure ratio (2.8:1) which was evaluated to determine the effect of lower density air in the fan stream on jet noise. Take-off with the reduced fan pressure ratio requires a higher level of thrust augmentation in the duct-burner. This is indicated in column B by the higher jet exhaust temperatures in the bypass stream. For the LBE, the two power settings listed in columns C and D were evaluated for noise characteristics.

The resulting noise estimates for these two engines are summarized in Tables 3.2-X, XI and XII. Normalized 90 EPNdB noise contours are shown for the VSCE in Figure 3.2-24. A noise contour comparison between the unsuppressed LBE and the VSCE with the coannular nozzle noise benefit is shown in Figure 3.2-25. The contours in this figure are normalized to the unsuppressed VSCE contours shown in Figure 3.2-24. The noise comparison shown in Figure 3.2-25 has special significance because the TOGW levels of these two engines are approximately equal as shown in Table 3.2-IX.

3.2.3.2 Conclusions

When these various types of engines are throttled and sized to meet FAR 36 without jet noise suppressors and without allowing for the potential noise benefit from coannular nozzles (Tables 3.2-VII and 3.2-VIII and Figure 3.2-23):

- The VSCE concept has the lowest TOGW, 760,000 lbs (345,000 kg); the conventional LBE has the next lowest, 800,000 lbs (360,000 kg).

TABLE 3.2-IX
NOISE-RELATED ENGINE OPERATING CONDITIONS FOR SUPPRESSED NOISE ESTIMATES

Engine Type	VSCE						LBE					
Power Setting	A			B			C			D		
Station	Sideline	Community	Approach	Sideline	Community	Approach	Sideline	Community	Approach	Sideline	Community	Approach
Fan Pressure Ratio	3.3	3.3	2.1	2.8	2.8	2.1	3.3	3.1	2.0	3.3	3.3	2.1
Total Engine Airflow ~lbs/sec (kg/sec)												
Unsuppressed	780 (355)	–	–	780 (355)	–	–	–	–	–	–	–	–
Suppressed	815 (370)	–	–	815 (370)	–	–	880 (400)	–	–	710 (320)	–	–
TOGW ~lbs (kg)												
Unsuppressed*	700,000 (315,000)	–	–	700,000 (315,000)	–	–	–	–	–	–	–	–
Suppressed	722,000 (330,000)	–	–	722,000 (330,000)	–	–	800,000 (360,000)	–	–	710,000 (320,000)	–	–
Jet Velocities ~ft/sec (m/sec)												
Fan	2,250 (690)	1,460 (450)	960 (280)	2,250 (690)	1,500 (460)	960 (280)	–	–	–	–	–	–
Engine	1,370 (420)	1,360 (420)	480 (146)	1,270 (390)	1,270 (390)	480 (146)	2,250 (690)	1,710 (520)	760 (230)	2,540 (770)	1,930 (590)	790 (240)
Jet Temperatures ~°F (°C)												
Fan	1,600 (870)	530 (277)	240 (116)	2,100 (1,150)	780 (416)	240 (116)	–	–	–	–	–	–
Engine	1,200 (650)	1,200 (650)	810 (430)	1,230 (660)	1,230 (660)	810 (430)	1,590 (865)	990 (530)	520 (271)	2,040 (1,115)	1,140 (615)	520 (271)

*These unsuppressed TOGW levels also apply to the VSCE with the coannular nozzle noise benefit.

TABLE 3.2-X

EPNdB NOISE ESTIMATES(1) FOR VSCE – UNSUPPRESSED, SUPPRESSED DUCT STREAM AND COANNULAR NOZZLE NOISE BENEFIT

POWER SETTINGS CORRESPONDING TO COLUMN A IN TABLE 3.2-IX

Noise Station		Sideline		Community With Cut-Back		Approach		Traded Noise Including/Excluding Approach	
Noise Estimate Based On / Level of Acoustic Treatment(2)		1	2	1	2	1	2	1	2
No Suppressor	Jet	117.0	117.0	114.0	114.0	103.0	103.0		
	Fan	96.0	95.0	105.5	104.5	112.5	111.5	117/117.5	116/117
	Total	118.0	118.0	116.5	116.0	115.5	114.5		
Suppressor(3) in Duct Stream Only	Jet	106.0	106.0	111.0	111.0	103.0	103.0		
	Fan	96.0	95.0	105.5	104.5	112.5	111.5	114/112.5	113/112
	Total	108.0	108.0	114.5	114.0	115.5	114.5		
Coannular(3) Nozzle Noise Benefit	Jet	108.0	108.0	108.0	108.0	103.0	103.0		
	Fan	96.0	95.0	105.5	104.5	112.5	111.5	114/111	113/110.5
	Total	109.5	109.5	112.5	111.5	115.5	114.5		

(1) Noise estimates are for four engines and allow for fuselage shielding and ground attenuation effects.

(2) Assuming low noise, near-sonic inlets and acoustically treated ducts as described in Table 3.2-VI.

(3) Includes the effect of acoustically treated ejector.

TABLE 3.2-XI

EPNdB NOISE ESTIMATES FOR VSCE ENGINE – UNSUPPRESSED, SUPPRESSED DUCT STREAM AND COANNULAR NOZZLE NOISE BENEFIT(1)

POWER SETTINGS CORRESPONDING TO COLUMN B IN TABLE 3.2-IX

Noise Station		Sideline		Community With Cut-Back		Approach		Traded Noise Including/Excluding Approach	
Noise Estimates Based On / Level of Acoustic Treatment(2)		1	2	1	2	1	2	1	2
No Suppressor	Jet	115.0	115.0	113.0	113.0	104.5	104.5		
	Fan	95.0	94.0	103.5	102.5	112.5	111.5	116/115.5	116/115.5
	Total	116.0	116.0	115.0	115.0	116.0	115.0		
Suppressor in(3) Duct Stream Only	Jet	102.5	102.5	108.5	108.5	104.5	104.5		
	Fan	95.0	94.0	103.5	102.5	112.5	111.5	114/110	113/109.5
	Total	105.0	105.0	112.0	111.5	116.0	115.0		
Coannular(3) Nozzle Noise Benefit	Jet	106.0	106.0	107.0	107.0	104.5	104.5		
	Fan	95.0	94.0	103.5	102.5	112.5	111.5	114/110	113/109.5
	Total	108.0	107.5	111.5	111.0	116.0	115.0		

(1) Noise estimates are for four engines and allow for fuselage shielding and ground attenuation effects.

(2) Assuming low noise, near-sonic inlets and acoustically treated ducts as described in Table 3.2-VI.

(3) Includes the effect of acoustically treated ejector.

TABLE 3.2-XII

EPNdB NOISE ESTIMATES FOR LOW BYPASS ENGINE (LBE 416) – UNSUPPRESSED AND SUPPRESSED FOR THE TWO POWER SETTINGS LISTED IN COLUMNS C AND D IN TABLE 3.2-IX[1]

POWER SETTINGS CORRESPONDING TO COLUMN C IN TABLE 3.2-IX

Noise Station		Sideline	Cutback	Approach	Traded Noise: Including Approach / Excluding Approach
No Suppressor	Jet	119.0	118.5	96.5	
	Fan	89.5	99.0	109.5	118 / 119.5
	Total	119.5	119.5	112.5	
Multi-Tube[2]	Jet	104.0	106.5	96.5	
Suppressor	Fan	89.5	99.0	109.5	111 / 107.5
	Total	105.5	109.5	112.5	

POWER SETTINGS CORRESPONDING TO COLUMN D IN TABLE 3.2-IX

Noise Station		Sideline	Cutback	Approach	Traded Noise
No Suppressor	Jet	121.5	122.5	97.5	
	Fan	89.5	99.0	109.5	122 / 123
	Total	122.0	123.5	112.5	
Multi-Tube[2]	Jet	108.5	108.5	97.5	
Suppressor	Fan	89.5	99.0	109.5	111 / 110
	Total	109.5	110.5	112.5	

(1) Noise estimates are for four engines and allow for fuselage shielding and ground attenuation effects.

(2) Includes the effect of acoustically treated ejector.

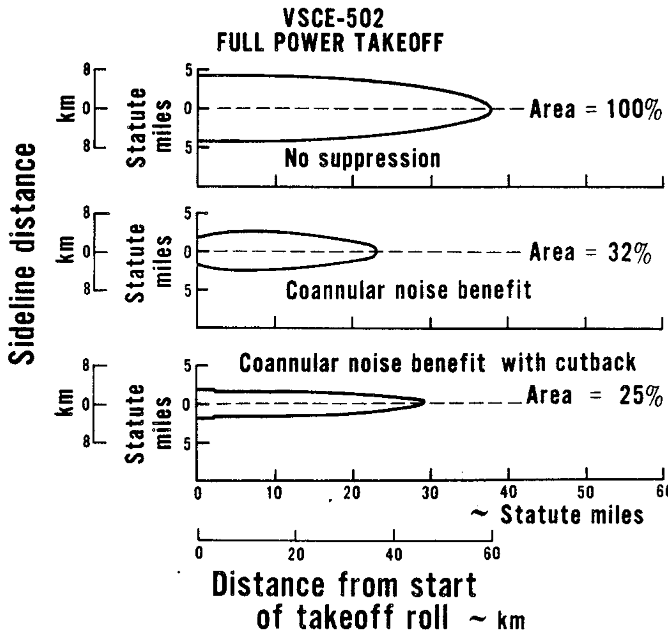


Figure 3.2-24 VSCE-502 90 EPNdB Noise Contours, Full Power Take-Off

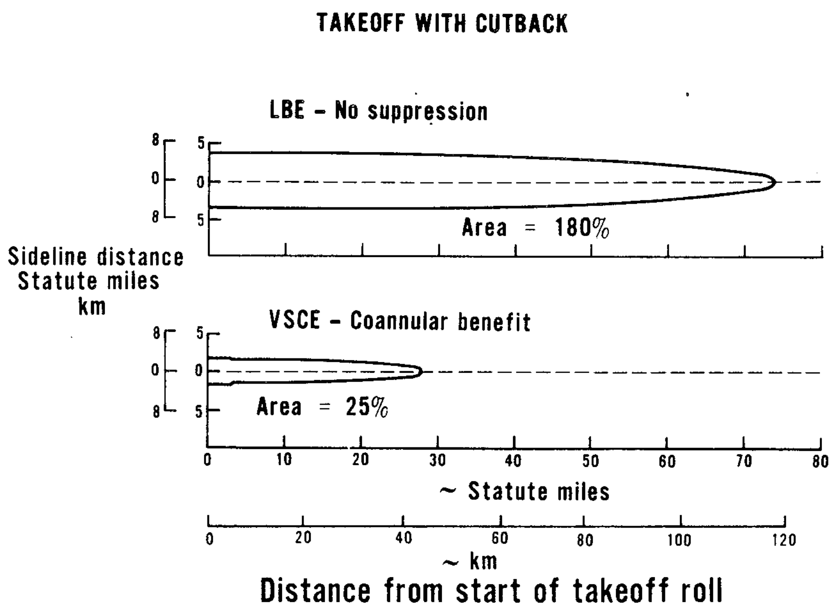


Figure 3.2-25 Comparison of 90 EPNdB Noise Contours for LBE and VSCE Cycles

- The valved VCE engines, because of their excessive weight, are not competitive. This is indicated by TOGW levels of 900,000 lbs (410,000 kg) and higher.

- Approach noise for each type of engine is well above the sideline and community levels. Several areas require further investigation to reduce approach noise relative to the other stations, including: a two segment operating procedure for approach; more detailed evaluation of "tuned" acoustic treatment; reducing fan source noise by incorporating low noise design features in the fan (e.g., increasing the axial spacing between rows of airfoils beyond the 50% assumed here may reduce fan noise by 3 PNdB); and the possibility of reducing engine power and using augmentation during approach, as described in Section 4.3.2.

- Traded noise levels are inconclusive at this stage of the AST propulsion studies because of the dominance of approach noise. When approach noise is excluded, traded noise levels shown in the last column of Table 3.2-VIII indicate a small (1 EPNdB) advantage of the LBE configuration relative to the other engines. This is because of the unusually high L/H level for the acoustic treatment (Table 3.2-VI). Because no weight or pressure loss penalty was included in this evaluation, this high level of treatment may not be practical and this approach noise advantage may not apply.

- The two levels of acoustic treatment (Columns 1 and 2 for each noise station in Table 3.2-VIII) show a small improvement in total noise levels at each station. This improvement is not considered to be significant enough to justify the complications of combining acoustic treatment with the duct-burner lining.

- The 90 EPNdB noise contours shown in Figure 3.2-23 for these unsuppressed engines vary from 26 to 35 square nautical miles (90 to 120 km^2). This narrow range readily illustrates that any of these engine concepts can be throttled to meet a certain footprint size. The dependent variable that determines the worth of each engine is TOGW. The valved VCE concepts shown in Tables 3.2-VII and 3.2-VIII and Figure 3.2-23 are not competitive, not because of noise characteristics, but because of their excessive weights which result in high TOGW levels.

When the VSCE concept is evaluated for the effect of jet noise suppressors applied to the duct stream only, and also for the potential noise benefit from coannular nozzles (Tables 3.2-IX, X and XI and Figures 3.2-24 and 3.2-25):

- The potential noise reduction from the coannular nozzle, when applied to the VSCE, yields the lowest TOGW. This is due to no weight or performance penalties associated with the coannular noise benefit.

- In contrast, jet noise suppressors applied to the bypass stream only, impose penalties to the engine in terms of extra weight, performance losses in the nozzle – both in the stowed and deployed positions – and overall complexity to the nozzle. Even though suppressors may have the capability of reducing jet noise more than the coannular benefit (by 2 EPNdB at sideline), these penalties cause higher TOGW levels.

- Application of a jet noise suppressor to the duct stream of the VSCE concept is considered a back-up to the potential noise benefit from coannular nozzles. Experimental wind-tunnel evaluation of the coannular benefit has commenced.

Data are expected from this program by the first quarter of 1976. At that time, the need for a back-up suppressor can be determined.

- The potential reduction in the 90 EPNdB footprint contours for the VSCE is very promising as shown in Figure 3.2-24. Relative to the unsuppressed engine, the coannular nozzle benefit has the potential to reduce the noise contour areas 32%. A further reduction to 25% is possible with power cut-back during take-off.

- There is a possible noise benefit associated with the VSCE engine at take-off for a reduced fan FPR and with higher augmentation to provide the required thrust (Tables 3.2-X and 3.2-XI). This is obtained with no increase in TOGW as shown in Table 3.2-IX. Further analysis of coannular noise and the dependence on duct stream temperature, density and velocity is required to confirm this benefit.

- The conclusions stated in the preceding section for approach noise, acoustic treatment and traded noise apply also to the VSCE with either a jet noise suppressor or with the coannular noise benefit.

For the Low Bypass Engine (LBE – Tables 3.2-IX and XII and Figure 3.2-25):

- The coannular noise benefit does not apply to the LBE configuration with a mixed-flow nozzle.

- An optimistic multi-tube suppressor was evaluated to reduce the noise to meet FAR 36. Relative to the unsuppressed LBE summarized in Table 3.2-VII (TOGW = 800,000 lbs (360,000 kg)), the suppressed engine yields approximately a 12% reduction in TOGW, as shown in Table 3.2-IX. Even with this optimistic suppressor, the TOGW for the LBE is higher than the VSCE.

- The two power settings listed in columns C and D of Table 3.2-IX show the effect of suppressed engine noise levels on engine size and TOGW. The sideline noise reduction of 4 EPNdB shown in Table 3.2-XII is accompanied by an increase in engine size and a significant increase (12%) in TOGW as shown in Table 3.2-IX. The noise information in Table 3.2-XII also indicates the ineffectiveness of a tube suppressor when take-off power is cut back to reduce community noise. As shown in Table 3.2-XII, there is only a 1 EPNdB reduction in total community noise for the two power settings in columns C and D.

- For approximately equal levels of TOGW, Figure 3.2-25 shows the 90 EPNdB noise contour advantage of the VSCE with the coannular nozzle noise benefit relative to the unsuppressed LBE.

The uncertain effects of flight on jet noise raise questions regarding the absolute estimates summarized in this section. Based on information contained in a recent AIAA paper(2), the jet noise levels in Tables 3.2-VIII, X, XI and XII may increase 1 to 3 EPNdB when the spectral and directional effects of flight on jet noise are accounted for. In general, the lower the jet velocity of the engine exhaust streams, the greater the increase in noise when flight effects are included. The industry is just beginning to understand the effects of flight on jet noise. Because the major objective of these propulsion studies is to compare and screen engine concepts on a relative basis, the fact that flight effects, other than relative jet velocities, have not been included does not alter the results of the Phase II study screening and engine selection process. Further studies will be required to assess the impact of these flight effects in absolute terms of engine size and TOGW for the most promising engine concepts. The Phase III study will include an assessment of flight effects as described in reference (2).

3.2.4 Emissions Estimates

The potential impact that advanced supersonic transports might have on the chemical balance of the stratosphere is a prime consideration of the AST propulsion study. Experimental research and study programs are being conducted by industry and federal agencies to determine the maximum acceptable emissions levels that can be released in the stratosphere by aircraft without adversely affecting the environment. These programs will eventually provide the background required to establish realistic emission regulations for advanced supersonic transports for operation in the stratosphere. Also, pollution restrictions in the airport vicinity will eventually be established. The recently released results from the Climatic Impact Assessment Program (CIAP) [4] indicate there are two pollutants of special concern at high altitudes (>40,000 feet): oxides of nitrogen (NOx) and sulphur dioxide (SO_2). Realistic emission regulations for these pollutants cannot be established for the stratosphere until intensive programs can be conducted over long periods of time to measure variations in the stratospheric composition and its sensitivity to both man-made and natural disturbances.

3.2.4.1 Experimental Clean Combustor Program

In the meantime, work has been started to reduce emissions released by future aircraft. NASA's Experimental Clean Combustor Program (ECCP – NAS3-16829) has initiated research and experimental programs of advanced combustor designs. These designs are being evaluated primarily for the main burners of engines that will power advanced subsonic airplanes and, in general, they will be applicable to the main burners of supersonic engines. An AST addendum was included in the ECCP to measure emission levels of these advanced burner concepts at test conditions simulating supersonic cruise operation. The intent of this AST addendum was to begin to evaluate innovations and advancements in combustion technology that will reduce emission levels for supersonic engines. The timing of this addendum is excellent in that advanced supersonic engines are in the early stages of study and can therefore be designed to accommodate new burner configurations. More of this type of combustion research is required at this early stage of the SCAR/AST program for both main burners and duct-burners. Sections 4.2 and 4.4 of this report describe program recommendations for these burner systems.

The two main objectives of the AST addendum were: to reduce NOx at high altitude supersonic flight conditions without compromising other main burner characteristics such as efficiency, stability and emission levels at other operating conditions; and to prepare conceptual combustor designs for the most promising advanced supersonic engines. Reductions in NOx levels were measured for three basic burner configurations. The three types of main burners that were evaluated for emission characteristics at simulated supersonic cruise conditions were the swirl can modular combustor, staged premix combustor and swirl Vorbix (vortex burning and mixing) combustor concepts. These combustor concepts are shown in Figures 3.2-26, -27 and -28, respectively, and described below.

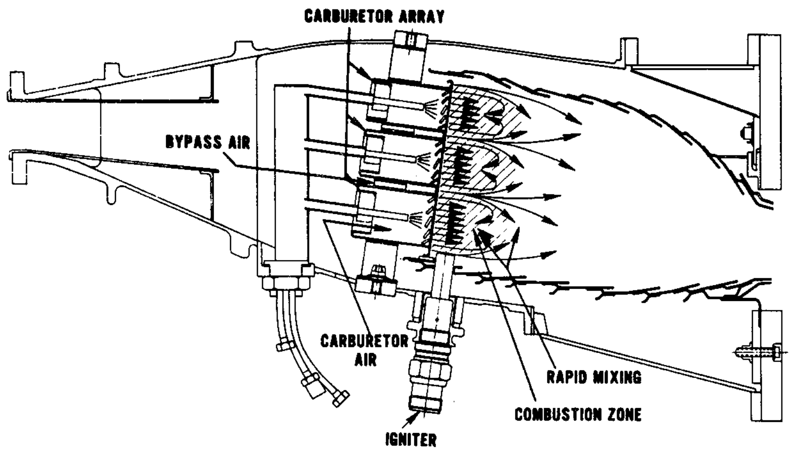


Figure 3.2-26 *Swirl Combustor Concept*

Swirl Can Modular Combustor (Figure 3.2-26)

This burner consists of an array of 120 swirl can modules positioned on three circumferential rows. Each module is constructed with three major components; a carburetor, a swirler and a flame stabilizer. Fuel is supplied through upstream injection tubes. Two fuel injector designs were evaluated, a conventional injection tube and a pressure atomizing injector.

After the premixing process, the modules are designed to swirl the fuel/air mixture and to stabilize combustion in their wake. In order to produce the desired rapid mixing of secondary air with the combustion gases, two major features are incorporated in the stabilizer design. First, a high degree of perimeter mixing is attained by using a flame stabilizer attached to each module. Second, since bypass air entering the array furthest from the combustion wakes is last to mix, blockage devices are provided between each module to force this air to flow closer to the combustion wakes. These blockage devices also provide discrete flow paths for flame propagation, thus enhancing the stability of the array.

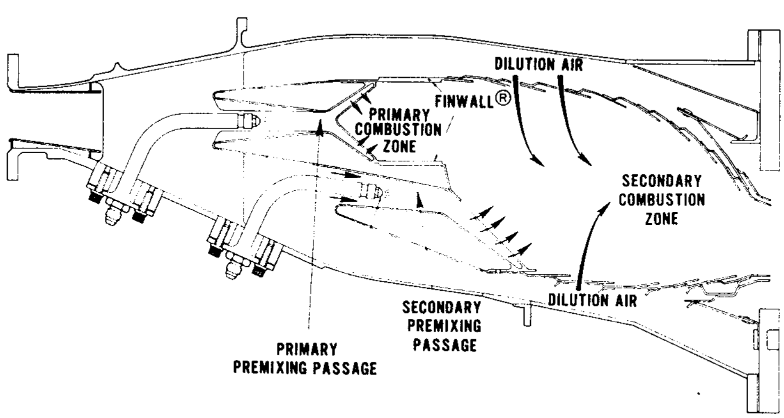


Figure 3.2-27 *Staged Premix Combustor Concept*

Staged Premix Combustor Concept (Figure 3.2-27)

The key characteristic of this burner is premixing of fuel and air prior to injection into the two separate combustion zones. The object is to control mixing uniformity and to improve the time-temperature characteristics of the combustion process in order to reduce emissions.

The combustor is made up of a primary system for low power operation and a secondary system for intermediate and high power operation. Each system has its own fuel injectors, premix passages, flameholders and combustion zones. The two premix passages and combustion zones are axially displaced with the primary combustion system upstream of the secondary system. This displacement reduces the quenching rate of the primary combustion process by the cool secondary air during low power operation. A high fuel source density in conjunction with pressure atomizing fuel injectors is used in both passages to promote fuel atomization, vaporization and premixing with air.

Power for idle and low thrust operation is provided by adding fuel to the primary system alone. The fuel/air ratio in the primary system is approximately stoichiometric at steady state idle operation. At a preset power level, the secondary fuel system becomes operative and the fuel is apportioned between both passages. The secondary system is ignited by the primary system. For full power, the fuel/air ratio in both passages is approximately 0.048.

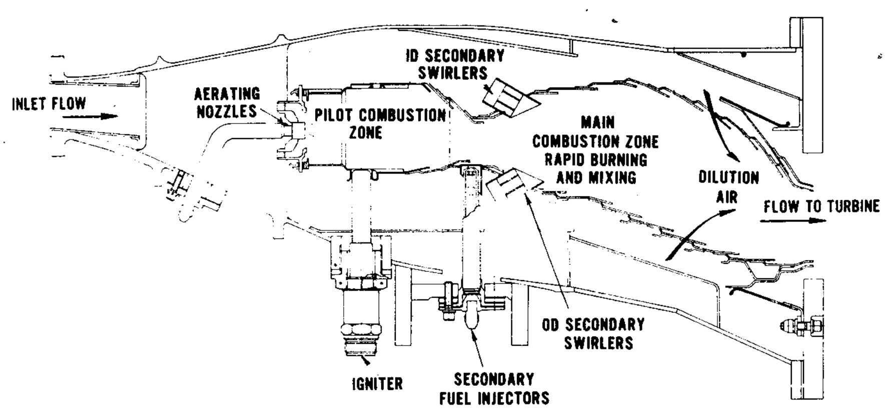


Figure 3.2-28 Swirl VORBIX Combustor Concept

Swirl Vorbix Combustor Concept (Figure 3.2-28)*

The swirl flow combustor employs the Raleigh instability of a swirling fluid interface to promote rapid mixing and combustion. NO_X formulation is low since the combustible mixture is not exposed to high temperature for as long a period of time as in conventional combustors.

*Vorbix = Vortex burning and mixing.

This design also employs two stages. Part of the fuel is burned in a pilot burner having a conventional design, while the remainder is burned in a centrifugal field produced by swirling secondary air jets. The hot gas from the pilot burner helps to vaporize and ignite the fuel which burns in the centrifugal field. The air and fuel flow splits are controlled so that only the pilot burner operates at the idle point.

Idle power emissions are minimized by: maintaining a high fuel/air ratio in the pilot, using aerating nozzles and by the application of an advanced configuration for the liners that delays the introduction of cooling air and thereby promotes complete combustion.

At higher power settings, secondary fuel is introduced through the injectors at the outer wall of the liner. Since the pilot discharge flow is partially vitiated, this secondary fuel does not burn immediately but vaporizes and mixes with the gas stream without combustion. Each secondary injector tube contains vanes which produce a strong swirling jet. The main combustion process, in which most of the fuel is burned for high power settings, proceeds in a very rapid manner at the interface between these jets and the surrounding fuel-rich jet mixtures from the pilot system. The rapidity of this process and the subsequent rapid quenching of the flow reduces the residence time in the high temperature zones so that NO_X formation is minimized.

3.2.4.2 ECCP Results

Some of the experimental results from these initial screening tests are summarized in Table 3.2-XIII. The goals set for the AST addendum are also tabulated. As indicated, none of the basic experimental configurations met the NOx goal for supersonic cruise operation. However, each configuration is close to the CO goal and one, the swirl can concept, is even lower.

The two configurations that were selected for modifications and for further testing were the swirl can modular concept and the swirl Vorbix concept. The staged premixed concept was not selected because it exhibited stability problems. Modifications were made to the two selected concepts to reduce NOx levels at supersonic operating conditions without compromising efficiency and emission levels at the other operating conditions.

The modifications made to these two experimental burner designs were based on previous ECCP test results which indicated that combustor velocity is a potent factor affecting NOx. Velocity is one of the parameters that controls the residence time of the combustion gases as they pass through the peak temperature zones. A velocity increase (residence time decrease) was accomplished by redesigning the burner liner contours for reduced flow areas.

TABLE 3.2-XIII

EXPERIMENTAL EMISSION MEASUREMENTS OF THREE MAIN BURNER COMBUSTOR CONCEPTS AT SIMULATED SUPERSONIC CRUISE CONDITIONS

		CONFIGURATION		
	GOALS	STAGED PREMIXED CONCEPT	SWIRL CAN MODULAR CONCEPT	SWIRL VORBIX CONCEPT
EMISSIONS INDEX**				
NO_X*	5	10.7	12.0	12.7
CO	5	7.1	4.7	6.5
THC	1	4.0	0.5	0.5
SAE SMOKE NO.	15	2	1	6
COMBUSTION EFFICIENCY (%)	≥99.8	99.4	99.8	99.8
TOTAL PRESSURE LOSS (%)	6-9	6.4	7.7	5.8
FUEL/AIR RATIO		0.0299	0.0265	0.0215

*NOT CORRECTED FOR INLET HUMIDITY

**POUNDS OF POLLUTANTS/1000 POUNDS OF FUEL AT SIMULATED SUPERSONIC CRUISE CONDITION (INLET TEMPERATURE = 1050°F (1510°R) AND INLET TOTAL PRESSURE = 100 PSIA (6.9×10^5 N/m²))

Some of the test results for the modified swirl Vorbix concept are listed in Table 3.2-XIV. This burner configuration demonstrated the lowest NOx levels at the simulated supersonic cruise conditions. At the reference velocity of 135 ft/sec (42 m/sec) which is the center column in Table 3.2-XIV, the modifications resulted in significant reductions in emissions relative to the initial levels shown in Table 3.2-XIII. NOx went from 12.7 to 9.5, CO from 6.5 to 4.5 and THC from 0.5 to less than 0.1. The reference velocity through the burner was varied over the range shown in Table 3.2-XIV to determine the impact of further variations in velocity and residence time interactions on emissions. As shown the trend as velocity is increased is lower NOx levels, but at the expense of reduced efficiencies and with increases in the other pollutants. Further research and evaluation of these advanced combustion technologies are required to meet all of the emission and operational improvements for advanced supersonic engines.

In the last phase of the AST addendum, the swirl Vorbix concept was applied to a main burner design for a representative AST study engine – the VSCE-502. Table 3.2-XV lists the basic combustion parameters for the swirl Vorbix main burner which were applied to this preliminary engine design. The engine cross-section in Figure 3.4-19 shows the swirl Vorbix main burner which has the same elements shown in the burner drawing of Figure 3.2-27. This burner concept was also applied to the duct-burner definition shown in the cross-section of Figure 3.4-19. Extending this main burner concept to the duct-burner is very preliminary in that the unique operating conditions for this duct-burner will undoubtedly require extensive modifications to the swirl Vorbix concept. However, this design definition is preferred over attempting to apply existing military engine augmentors (afterburners) which are designed for much higher fuel/air ratios and do not reflect the low jet noise requirement that is critical for these AST engines.

TABLE 3.2-XIV

EMISSION LEVELS FOR MODIFIED SWIRL COMBUSTOR CONCEPT
AT SIMULATED SUPERSONIC CRUISE CONDITIONS

	GOAL	SWIRL VORBIX COMBUSTOR		
REFERENCE VELOCITY FT/SEC		118	135	170
(M/SEC)		(36)	(41)	(52)
EFFICIENCY (%)		99.91	99.88	99.77
EMISSION INDEX (2)				
• NOx	5	11.8	9.5	8.5
• CO	5	3.6	4.5	9.4
• THC	1	0	<0.1	<0.1

(1) T_{IN} = 1050°F, (565.6°C) P_{TIN} = 100 PSIA (6.9 × 10^5 N/m^2)
(2) LBS PER 1000 LBS OF FUEL (GRAMS PER KILOGRAM)

TABLE 3.2-XV

COMBUSTION PARAMETERS OF MAIN SWIRL VORBIX BURNER
FOR REPRESENTATIVE AST ENGINE*

	Take-Off	Supersonic Cruise
Volumetric Heat Release Rate (BTU/hr – ft^3 – atm)		
Pilot Zone	4.0 X 10^6	4.0 X 10^6
Secondary Zone	8.0 X 10^6	8.0 X 10^6
Residence Time (Milliseconds)		
Pilot Zone	4.2	4.1
Secondary Zone	2.7	2.6
Combustion Pressure Loss (%)	3.0	3.4

*VSCE-502

3.2.4.3 Emission Estimates for Representative Variable Cycle Engines

Emission levels were estimated for the two most promising Variable Cycle Engines, the data pack version of the Variable Stream Control Engine (VSCE-502) and one of the parametric definitions of the rear-valve Variable Cycle Engine (VCE-110). At supersonic cruise, the ECCP data were extrapolated to the engine operating conditions and fuel/air flow rates in order to estimate emission levels for the primary burners. Each of these VCEs have duct-burners which operate at low fuel/air ratios for supersonic cruise. The ECCP main burners data are not close enough to the duct-burner pressures, temperatures and flow rates for direct extrapolation. Rather, experimental results from another emissions test program using the JT9D main burner at part power conditions were used for estimating duct-burner emissions.

Table 3.2-XVI summarizes the emission levels estimated for the main burner, the duct-burner and the total engine at supersonic cruise conditions. For comparison, the emission levels for a current technology engine at supersonic cruise are included. The procedure for scaling NOx test data to engine conditions was by the fundamental relationship of:

$$\left[\left(\frac{\text{burner inlet pressure}_{\text{engine}}}{\text{burner inlet pressure}_{\text{test}}}\right)\right]^{1/2} \cdot e\left(\frac{\text{burner inlet temperature}_{\text{engine}}}{\text{burner inlet temperature}_{\text{test}}}\right)$$

CO and THC were scaled inversely with pressure. As indicated in Table 3.2-XVI, NOx for the AST Variable Cycle Engines is approximately half the level for the current technology engines. This reduction was accomplished without compromising the CO and THC levels. There is, however, a penalty associated with this reduction in NOx. The ECCP burner concepts represent increased complexity over conventional burner designs. Extensive follow-on work is required to further reduce emission levels and to determine the minimum achieveable levels for emissions while retaining practical combustor designs suitable for commercial aircraft. The ultimate limits on emission reduction and the corresponding impact on other engine factors including cost, complexity, maintainability, stability, life, etc., will emerge from these continuing efforts.

The AST addendum of the ECCP did not include an evaluation of emission levels for the airport vicinity. In place of test data, hypothetical estimates of the emission levels for the VSCE concept were made. These estimates are shown in Table 3.2-XVII and are based on the following key assumption – that advanced combustion technology projected for future engines will meet the 1979 EPA parameters for subsonic engines. This same advanced combustion technology was applied to the VSCE-502 configuration. The first column of numbers in Table 3.2-XVII shows the 1979 emissions standards for future subsonic engines (EPA Class T2). The second column shows the emission levels obtained by applying the advanced combustion technology that meets the 1979 EPA parameters to the AST engine (Class T5). The third column lists the EPA parameters proposed for advanced supersonic engines (which are the same as the 1979 levels for subsonic engines). The last column indicates the additional reductions required for supersonic engines to meet these proposed 1981 EPA parameters. These numbers illustrate the pronounced influence that the supersonic engine cycle and the take-off and landing cycle for supersonic transports can have on emission levels. Even with the very advanced combustion technology projected in generating these numbers, the emission levels are approximately three times higher than the proposed 1981 EPA parameters for supersonic engines. Based on the comparison shown in Table 3.2-XVII, it is concluded that advanced supersonic engines will require more advanced, low emissions technology than advanced subsonic engines. Table 3.2-XVIII lists the adverse (and beneficial) factors that cause advanced supersonic engines to require more advanced combustion technology.

TABLE 3.2-XVI

EMISSION ESTIMATES FOR TWO AST VARIABLE CYCLE ENGINES AT SUPERSONIC CRUISE

Emission Index(1)

	VSCE-502			Rear Valve VCE-110		
	Main Burner	Duct Burner	Total Engine	Main Burner	Duct Burner	Total Engine
NOx	13.7	6.3	9.3	20.7	9.1	11.3
CO	3.4	5.7	4.5	2.7	4.2	3.8
THC	0	0.1	0.1	0	0.1	0.1

Current Technology Supersonic Engine(2)

	Total Engine
NOx	18 - 19
CO	1 - 5
THC	1

(1) Lbs. of Emissions per 1000 lbs. of Fuel (g per kg)

(2) NASA TMX-71509, "Forecast of Jet Engine Exhaust Emissions for Future High Altitude Commercial Aircraft" by Jack Grobman and Robert D. Ingebo.

Based on emission estimates reviewed in this section for high altitude operation and also around the airport, advanced combustion technology is a critical requirement for both the main burners and the duct-burners of Variable Cycle Engines for advanced supersonic transports.

TABLE 3.2 - XVII

COMPARISON OF EPA STANDARDS*
FOR ADVANCED SUBSONIC AND SUPERSONIC ENGINES

Pollutant	1979 subsonic (Class T2) engines	Combustor meeting 1979 subsonic EPA standard applied to AST engine (Class T5)	Proposed 1981 supersonic (Class T5) engines	Additional% reduction required for supersonic engines
NO_x	3.0	7.3	3.0	59%
CO	4.3	15.9	4.3	73%
THC	0.8	3.0	0.8	73%

* Lbs. of pollutant per 1000 lbs. of thrust - hours per cycle

TABLE 3.2-XVIII

FACTORS AFFECTING AST ENGINE EMISSIONS
RELATIVE TO SUBSONIC ENGINES

Adverse Factors

- Lower Bypass Ratios (in the range from 1.0 to 2.5) result in 100% higher TSFC for AST engines at take-off.
- Thrust augmentors will require special technology to meet low emission levels.
- Designing combustor systems for low NOx at supersonic cruise operation may compromise burner characteristics and emission levels at other operating conditions.
- Take-off and Landing Operating cycle is more severe for supersonic transports in that it includes a low power (15%) descent period and a longer take-off time (1.2 minutes versus 0.7 minutes).

Beneficial Factors

- Lower overall pressure ratios result in lower temperatures into the main burner during take-off and subsonic operation. This will reduce NOx for these operating conditions.
- Low pressures and temperatures into the augmentors in bypass streams may ease the NOx characteristics of these burner systems.

3.3 SYSTEM SENSITIVITY STUDIES

Most of the Boeing and P&WA engine comparisons were based on evaluations in baseline aircraft configurations and a mid-range cruise Mach number. Boeing evaluations were based on a fixed 750,000 lb (340,000 kg) modified delta wing aircraft and then a blended wing configuration. P&WA evaluations were based on a scaled modified arrow wing aircraft. Both system studies used a nominal 2.4 cruise Mach number. In order to determine the impact of airplane ground rules on engine selection, sensitivity studies were conducted.

For the P&WA sensitivity studies, the basic scaled NASA Reference Aircraft configuration was retained; but variations in wing loading were examined around the mid-range cruise Mach number. The baseline aircraft configuration was then examined over a range of cruise Mach numbers from 2.2 to 2.7.

A Boeing study was conducted to determine the impact of changes in airplane cruise Mach number and airplane drag level. The baseline modified delta wing airplane configuration and the VSCE-502 were used for the cruise Mach number study. For the airplane drag level study, three different airplane configurations with major differences in wing loading, aspect ratio, wing platform, etc., were analyzed with the VSCE-502 engine. Propulsion pod drag sensitivities were analyzed by Boeing on the baseline configuration.

3.3.1 P&WA Sensitivity Studies

3.3.1.1 Wing Loading

In order to assess the impact of wing loading on TOGW, it was necessary to estimate the influence of wing loading on aircraft Operating Empty Weight (OEW) and airplane aerodynamics. An equation expressing airplane OEW as a function of wing loading, TOGW, and pod weight was provided by NASA-Lewis. The effect of wing loading on aerodynamics was estimated by P&WA. Results are shown in Figure 3.3-1, based on the VSCE-502 installation characteristics. Two different engine sizing criteria were evaluated. The solid line represents engine operation at a fixed power setting (i.e., constant noise) and a fixed take-off field length for each value of wing loading. To maintain constant power setting and field length, the engine size must be increased as wing loading increases. With this engine sizing criteria, the baseline wing loading appears to be close to optimum. The dashed line represents constant airflow/TOGW engine sizing, which implies: for constant noise (i.e., power setting) the take-off field length will increase with increasing wing loading; or for constant field length, the power setting (i.e., sideline jet noise) will increase with increasing wing loading. Constant airflow/TOGW engine sizing results in significant TOGW decreases with increasing wing loading. However, increases in wing loading also correspond to increases in landing speed; therefore, if the potential TOGW reduction due to increased wing loading is to be realized, take-off and landing aerodynamics must be improved.

The effect of wing loading on TOGW was also examined for the LBE-405. The results shown in Figure 3.3-2 are similar to those obtained for VSCE-502, except that the benefits due to increased wing loading are not quite as large. This is due to the relatively flat shape of the supersonic part power curve of LBE-405 relative to VSCE-502.

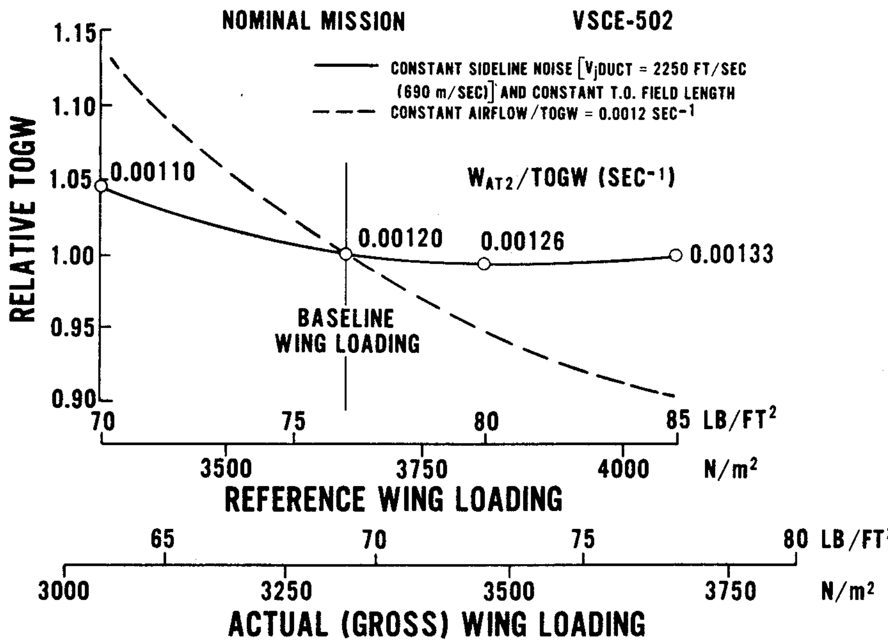


Figure 3.3-1 Wing Loading Effect on TOGW for VSCE-502

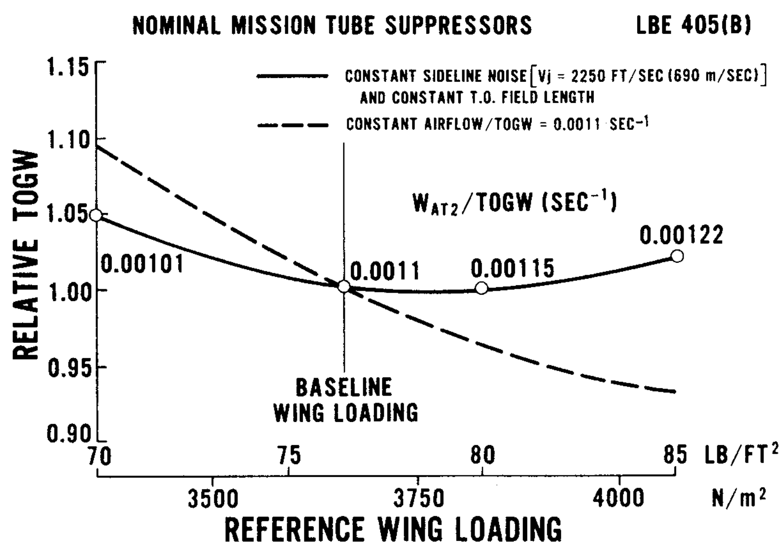


Figure 3.3-2 Wing Loading Effect on TOGW for LBE-405B

The effect of airplane wing loading on the engine/airplane cruise match for the VSCE-502, with constant power setting sizing, is illustrated in Figures 3.3-3, 3.3-4 and 3.3-5. The impact of wing loading and cruise altitude on cruise lift/drag is shown in Figure 3.3-3. Increasing wing loading shifts the airplane maximum lift/drag to a lower altitude. The effect of wing loading on the airplane drag polar was based on a P&WA analysis, the result of which indicates that for the range of wing loadings studied, there is little change in the maximum lift/drag. These results were obtained using the NASA Langley Reference Configuration as the baseline airplane and assuming that the wave drag (D/q) was proportional to the square of the maximum equivalent body area (S_{max}^2). Inlet drag (spillage, bypass, and boundary layer bleed) and nozzle drag are included in the engine performance, while nacelle wave drag and skin friction are included in the airplane drag.

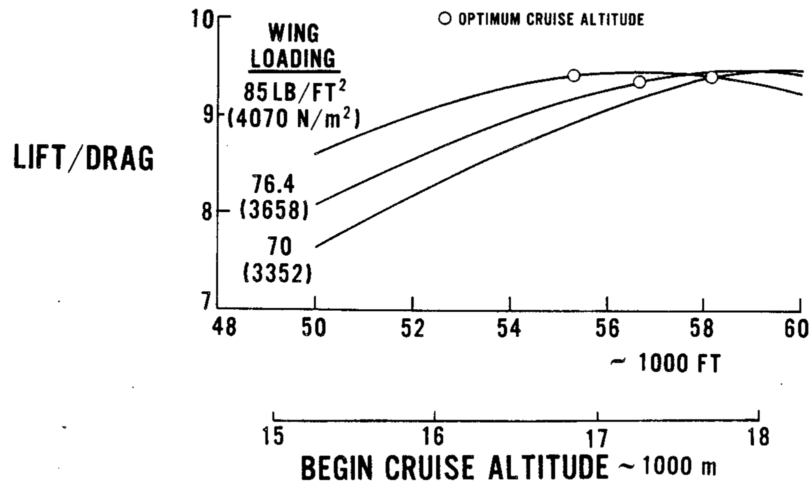


Figure 3.3-3 Wing Loading Effect on Lift/Drag

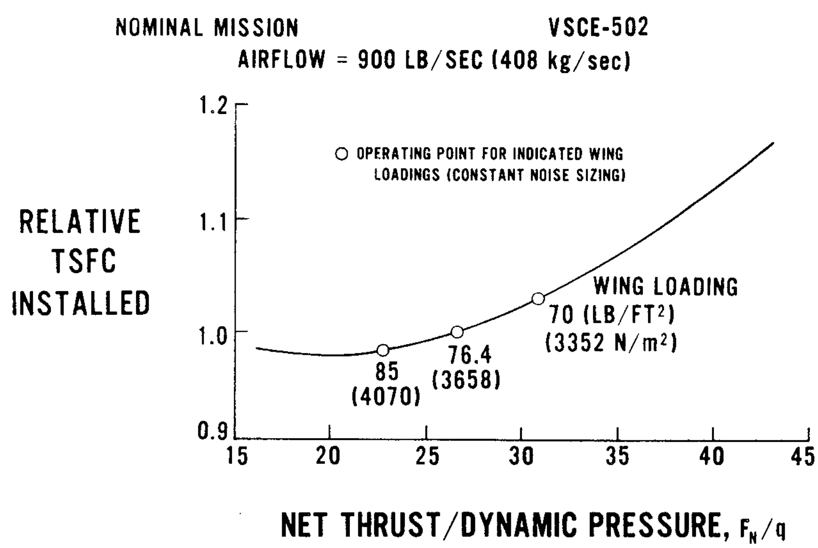


Figure 3.3-4 Wing Loading Effect on Engine Cruise Power Setting for VSCE-502

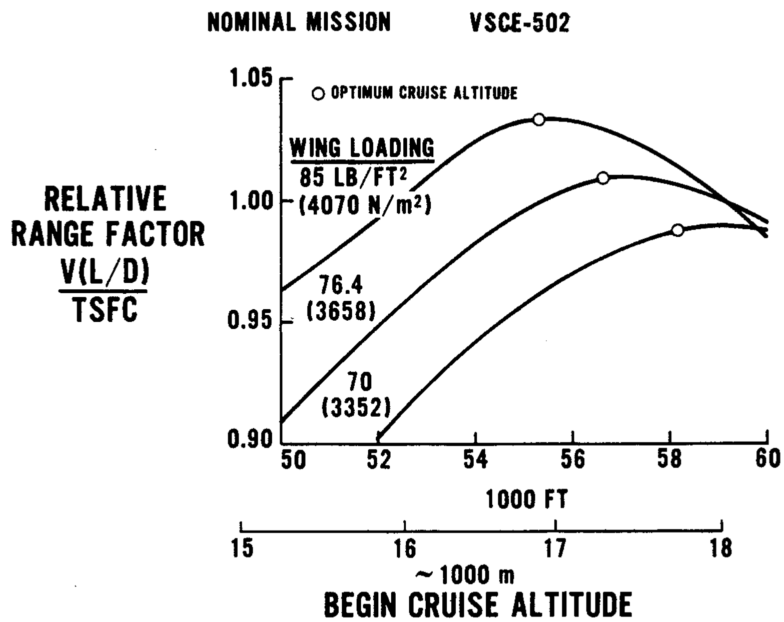


Figure 3.3-5 *Wing Loading Effect on Range Factor for VSCE-502*

The supersonic cruise part power curve for the VSCE-502 is shown in Figure 3.3-4 with thrust normalized by free stream dynamic pressure. The operating points for maximum range are shown for several wing loadings. Because the altitude for maximum lift/drag decreases with increasing wing loading and engine thrust increases with decreasing altitude, the cruise power setting decreases with increasing wing loading. This results in improved TSFC of the VSCE-502 with increasing wing loading. A wing loading of 85 lb/ft^2 (4070 N/m^2) or higher permits cruise operation very near the minimum TSFC.

The effect of wing loading on supersonic cruise range factor is shown in Figure 3.3-5. Increased wing loadings resulted in improved TSFC due to operation closer to the minimum TSFC point on the part power curve, as shown on the previous figure. Since the maximum lift/drag did not decrease significantly with increasing wing loading, the range factor improved. This results in a 3% improvement in range factor for the 85 lb/ft^2 (4070 N/m^2) wing loading compared to the baseline wing loading of 76.4 lb/ft^2 (3660 N/m^2). Further increases in wing loading will not improve the range factor further because at W/S=85 lb/ft^2, (4070 N/m^2), cruise operation is near minimum TSFC and maximum L/D.

Based on the results of this study, it has been concluded that increased wing loadings permit a better airplane/engine cruise match; however, take-off and landing aerodynamic improvements may be required to realize the potential benefits of reduced wing size.

3.3.1.2 Cruise Mach Number

The VSCE-502 and LBE-405 were evaluated in the NASA Langley Reference Aircraft at Mach number 2.12, 2.32, and 2.62 (STD+8°C). The aircraft configuration or structure weight were not varied with Mach number, so that the results do not necessarily reveal the optimum cruise Mach number. The study was intended to reveal differences in engine characteristics as affected by Mach number. The results (Figure 3.3-6) show that VSCE-502 has a lower TOGW than LBE-405 over the entire Mach number range, with a greater advantage as cruise Mach number increases.

The engine cycle in the above study was also held constant with cruise Mach number. The matrix of LBE's described in Section 3.1.3.2 were also evaluated at Mach number 2.12, the result being that the BPR of the LBE-405 cycle has the advantage over the other LBE cycles at the lower Mach number. However, it may be desirable to increase the OPR of both the VSCE-502 and LBE-405 as cruise Mach number is reduced, especially for the mixed mission where subsonic TSFC becomes more significant.

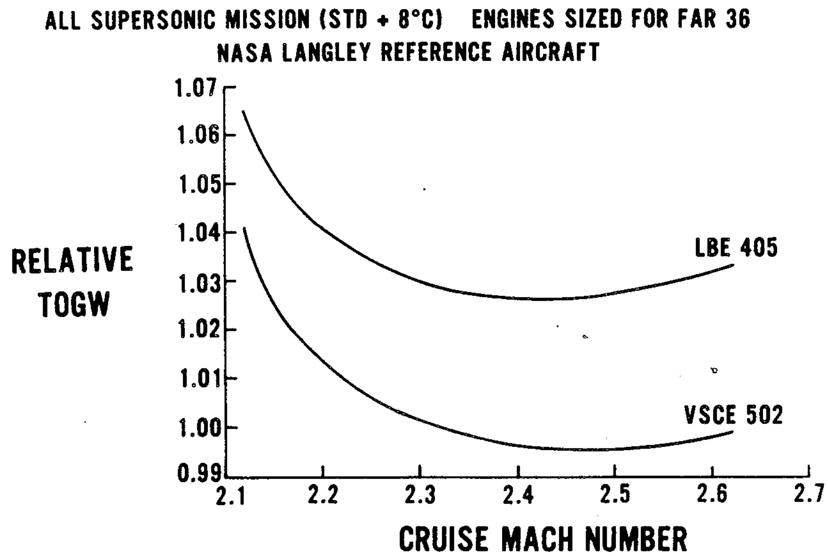


Figure 3.3-6 Supersonic Cruise Mach Number Effects

3.3.2 Boeing Sensitivity Studies

3.3.2.1 Cruise Mach Number

The parametric study results of the effects of cruise Mach number on the optimum VSCE-502 engine size are summarized in Figure 3.3-7. Best range occurs at all Mach numbers at an engine size slightly larger than 800 lb/sec (360 kg/sec). Mach 1.1 thrust margin is adequate at that engine size. The optimum engine size increases only slightly with increasing Mach number. This is because the best cruise altitude tends to increase with increasing Mach number, which requires slightly larger engines for best range.

A detailed breakdown is given in Table 3.3-I of the mission fuel buildups and associated range increments for a VSCE-502 engine size of 810 lb/sec (360 kg/sec). Increasing the cruise Mach number results in a range loss during supersonic climb, but a range increase in cruise and descent. Mach 2.32 cruise range is 68 nmi (126 km) greater than Mach 2.12 cruise range and only 9 nmi (16.7 km) less than Mach 2.62 cruise. Block time and subsonic leg performance are also given in Table 3.3-I. Subsonic leg performance is given as the $M^n = 0.9$ cruise range factor at a heavy gross weight (700,000 lb (318,000 kg)) relative to midcruise supersonic range factor. As the supersonic cruise velocity increases, the supersonic cruise range factor increases slightly while the subsonic range factor is unchanged. This causes the subsonic/supersonic performance match to be slightly degraded with increasing supersonic cruise speed.

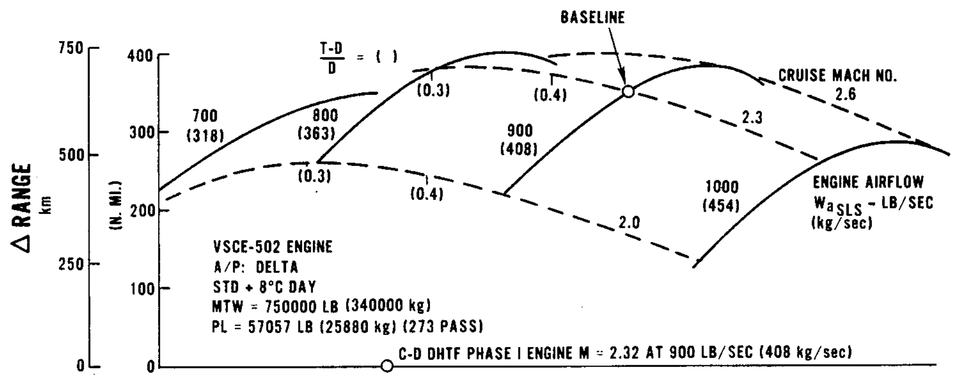


Figure 3.3-7 VSCE-502 Cruise Mach Number Sensitivity

3.3.2.2 Airplane Drag Characteristics

Figure 3.3-8 summarizes the results of the range sensitivity study to identify the impact of rematching the VSCE-502 engine to planforms which have different subsonic, transonic, and supersonic drag characteristics. Planform designated "A" represents a configuration which has been optimized for high supersonic cruise L/D. Planform "B" is a delta wing planform which has been optimized for minimum transonic drag and retains the high cruise L/D of Planform "A". Planform "C" has compromised the high supersonic L/D for improved low speed characteristics, and is the baseline delta wing airplane.

In order to present the range impact due to engine matching, the OEW of each planform was adjusted so that all planforms were normalized to the same range with a 900 lb/sec (408 kg/sec) size engine in Figure 3.3-8. At the 900 lb/sec (408 kg/sec) size, the OEW (required for constant range) was determined for each drag level and the engine size was varied to determine the effect on range and thrust margin. For the best range, the Planform B drag level requires the smallest engine (725 lb/sec (330 kg/sec)), while Planform A drag level requires the largest engine size (835 lb/sec (390 kg/sec)). The transonic climb thrust margins are adequate. Subsonic and supersonic cruise comparisons are shown in Figure 3.3-9. The supersonic cruise range factor (900 lb/sec (408 kg/sec)) is highest for Planform B (lowest cruise altitude). The range factor for Planform A is 2 percent lower and the cruise altitude is 3000 feet (910m) higher. The Planform C range factor is 6 percent lower. The engine size for the best supersonic cruise match illustrates the differences in best cruise altitude and L/D for each planform.

TABLE 3.3-I
RANGE INCREMENTS AND MISSION FUEL BUILD-UP EFFECT OF CRUISE MACH NUMBER

MTW = 750,000 lb (340192 kg)
OEW = 336,160 lb (152479 kg)
P/L = 57,057 lb (25880 kg) (273 pax.)
STD + 8°C Day
W_a = 810 lb/sec
VSCE-502 Engine

		M_{cruise} = 2.12	M_{cruise} = 2.32		M_{cruise} = 2.62	
Δ Range, N.MI. (km)				+68 (126)		+77 (143)
Taxi & Takeoff	Fuel, ~lb.	6354	6354	0	6354	0
	(kg)	(2880)	(2880)		(2880)	
Subsonic Climb	Fuel, ~lb.	21464	21464	0	21464	0
	(kg)	(9740)	(9740)		(9740)	
	Dist., ~N.MI.	92	92		92	
	(km)	(170)	(170)		(170)	
Supersonic Climb	Fuel, ~lb.	56012	63450	−33 (−61)	75170	−76 (−141)
	(kg)	(25400)	(78780)		(34100)	
	Dist., ~N.MI.	283	332		417	
	(km)	(524)	(615)		(772)	
Cruise @ 550 klb.	LD/LD_{max}	8.26/8.62	7.98/8.37		7.57/8.03	
	TSFC ~ lb/hr/lb	1.4565	1.496	+88 (163)	1.587	+116 (215)
	(kg/hr/N)	(0.149)	(0.153)		(0.162)	
	MN	2.12	2.32		2.62	
Descent + ILS	Fuel, ~lb.	3822	3989	+13 (24)	4232	+37 (69)
	(kg)	(1734)	(1809)		(1920)	
	Dist., ~N.MI.	167	183		211	
	(km)	(309)	(339)		(391)	
Reserves	Fuel, ~lb.	48076	48076	0	48076	0
	(kg)	(21810)	(21810)		(21810)	
$RF_{Subsonic}/RF_{Supersonic}$		1.100	1.069		1.060	
Block Time, hr.		3.467	3.322		3.092	
Relative Block Fuel/Pass	Mi~lb/Pass N.MI.	1.00	0.98		0.98	
	(kg/Pass km)	(0.245)	(0.240)		(0.240)	

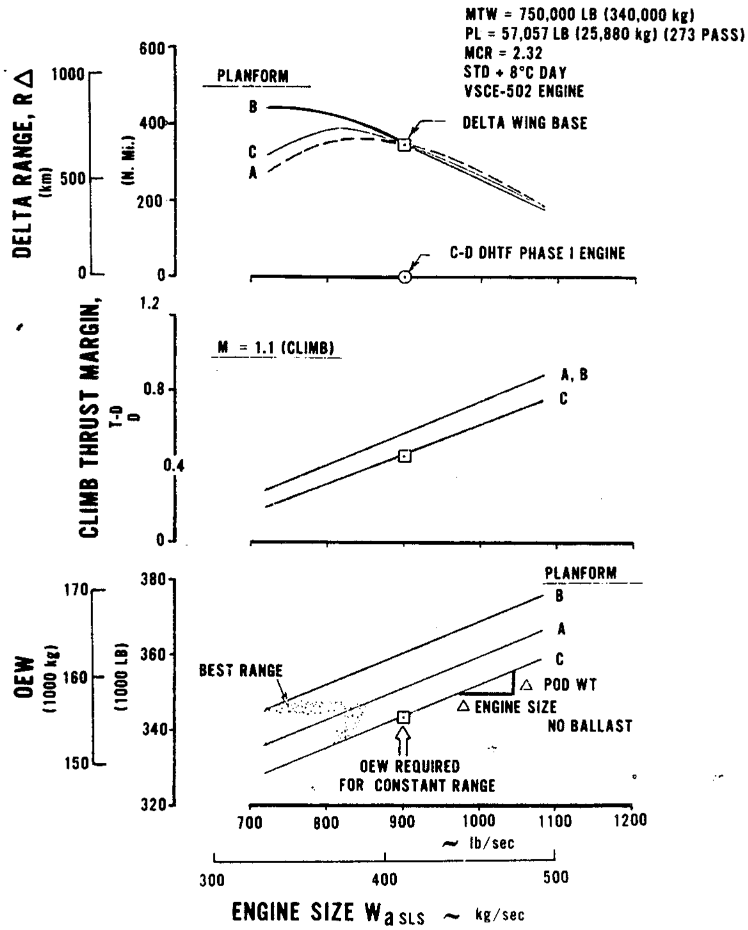


Figure 3.3-8 Drag Sensitivity for VSCE-502

The subsonic cruise comparison (900 lb/sec (408 kg/sec)) shows that Planform B has the best range factor. The engine size for best subsonic cruise match is about 700 lb/sec (310 kg/sec) for Planforms B and C and 800 lb/sec (360 kg/sec) for Planform A. These engine sizes represent the ideal engine match provided climb and supersonic cruise performance could be improved. The best supersonic/subsonic match occurs for Planform B at the same engine size of about 730 lb/sec (330 kg/sec). Climb thrust margins and TSFC for the VSCE-502 on the three configurations are given in Figure 3.3-10.

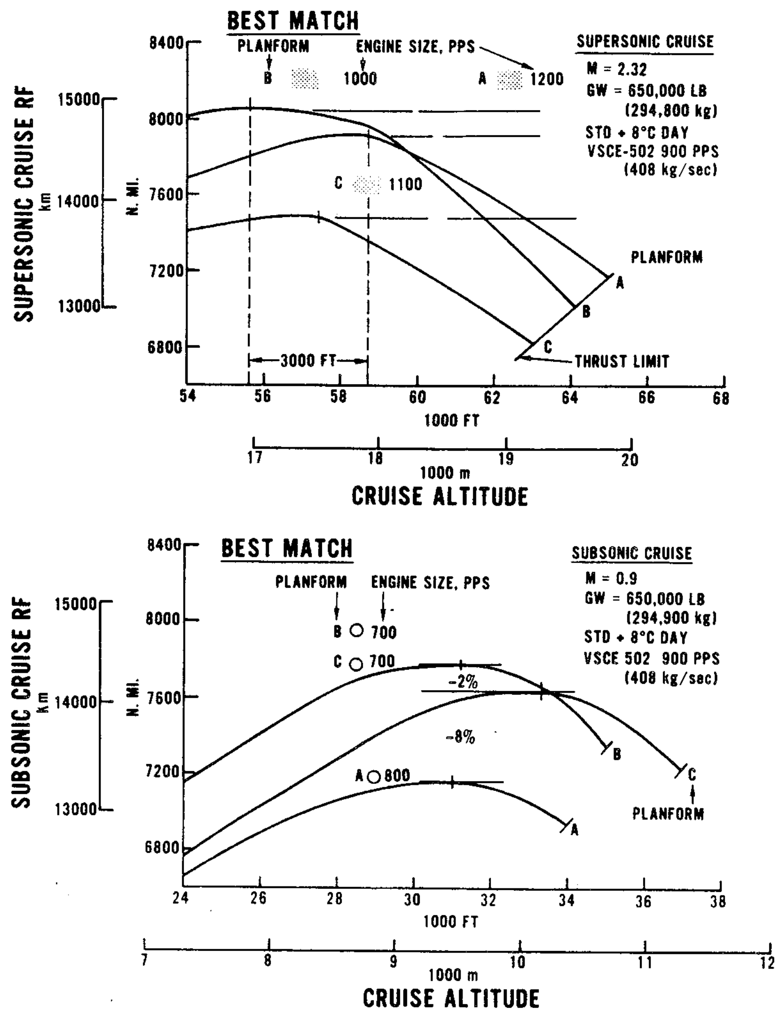


Figure 3.3-9 Cruise Match Comparison, VSCE-502

A detailed mission breakdown of the effect of configuration drag level on mission fuel and fuel efficiency is given in Table 3.3-II. These results are for constant range (OEW was adjusted to give constant range) at an engine size of 810 lb/sec (370 kg/sec). Planform A suffers penalties for subsonic climb, descent, and fuel reserves and has only a slight cruise advantage over Planform C. (Best supersonic cruise match occurs at an engine size of about 1200 lb/sec (540 kg/sec) for Planform A.) Planform B has a better supersonic/subsonic engine match at 810 lb/sec (370 kg/sec), and thus has a 310 nmi (570 km) range advantage (or 18,340 lb (8320 kg) OEW) over Planform C. In terms of pounds of fuel per passenger nautical mile, Planform B is 6 percent lower than Planform C (0.310 compared to 0.329) and 4 percent lower than Planform A.

TABLE 3.3-II
AIRPLANE PLANFORM EFFECTS ON OEW, MISSION FUEL, AND FUEL EFFICIENCY AT CONSTANT RANGE

MTW = 750,000 lb (340000 kg)
P/L = 57,057 lb (26000 kg) (273 pax)
STD + 8°C Day
M_{cruise} = 2.32
VSCE-502 Engine

W_a = 810 lb/sec (370 kg/sec)
Range = $R_{D/HTF\ C\text{-}D}$ + 378 N.M. (700 km) = Constant

		Planform C (Baseline)	Planform A	Δ R, N.MI. (km)	Planform B	Δ R, N.MI. (km)
OEW Required For $R = R_{D/HTF\ C\text{-}D}$ + 378 N.M. (700 km)	~ lb.	336160	341200	– 83	354500	– 310
	(kg)	(152480)	(154760)	(154)	(160800)	(574)
Taxi & Takeoff	Fuel, ~lb.	6354	6323	0	6354	0
	(kg)	(2880)	(2870)		(2880)	
Subsonic Climb	Fuel, ~lb.	21464	26323	– 52	20358	+7
	(kg)	(9740)	(11940)	(96)	(9230)	(13)
	Dist., ~N.MI.	92	105		87	
	(km)	(170)	(194)		(161)	
Supersonic Climb	Fuel, ~lb.	63450	60358	+20	54981	+50
	(kg)	(28780)	(27380)	(37)	(24940)	(93)
	Dist., ~N.MI.	332	321		289	
	(km)	(615)	(594)		(535)	
Cruise @ W = 550000 lb	LD/LD_{max}	7.98/8.39	8.37/8.95	+65 (120)	8.645/8.81	+236 (437)
	TSFC	1.496	1.497		1.497	
Descent + ILS	Fuel, ~lb.	3989	5165	– 15	4215	+8
	(kg)	(1809)	(2343)	(28)	(1912)	(15)
	Dist., ~N.MI.	183	189		195	
	(km)	(339)	(350)		(361)	
Reserves	Fuel, ~lb.	48076	49040	–18	47556	+9
	(kg)	(21810)	(22240)	(33)	(21570)	(17)
(T-D)/D @ M = 1.1		0.326	0.435		0.430	
Lb. Fuel/Pass. N.MI.		0.329	0.323		0.310	
(kg fuel/pass. km)		(0.081)	(0.079)		(0.076)	
$RF_{subsonic}/RF_{supersonic}$		7730/7231 = 1.069	7217/7581 = 0.952		7890/7826 = 1.008	

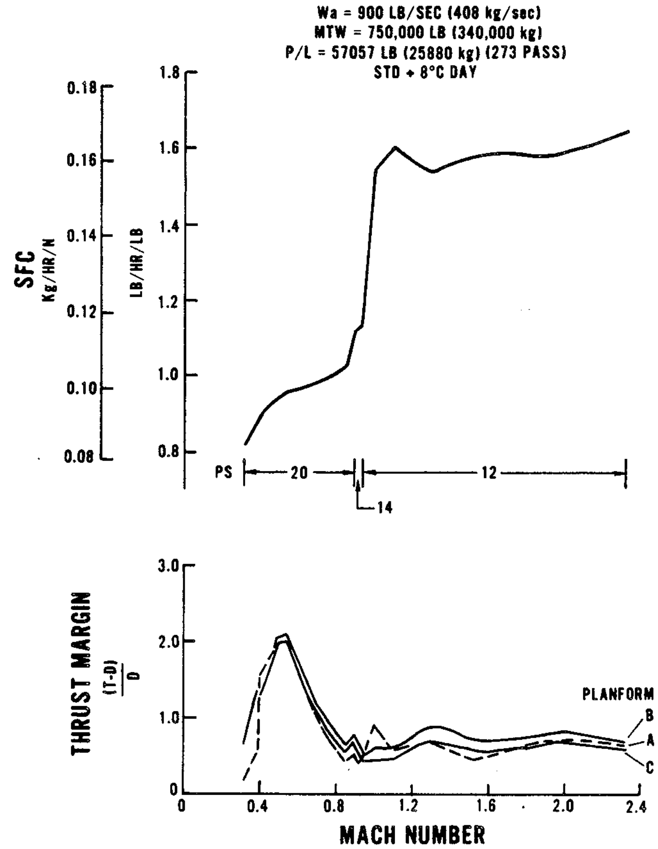


Figure 3.3-10 *Climb Performance – Drag Sensitivity, VSCE-502*

Subsonic leg capability is illustrated in Figure 3.3-11 at an airflow size of 810 lb/sec (370 kg/sec). Planform A has poor subsonic performance which degrades its range capability by 5 percent when flying subsonic legs. Planform B has a better match between supersonic/ subsonic performance due to its better subsonic L/D and actually increases its range capability slightly (1 percent) with subsonic legs. Planform C, the baseline delta wing design, has much poorer supersonic range factor than Planform B and essentially the same subsonic range factors, and hence increases its range capability substantially (7 percent) with subsonic legs.

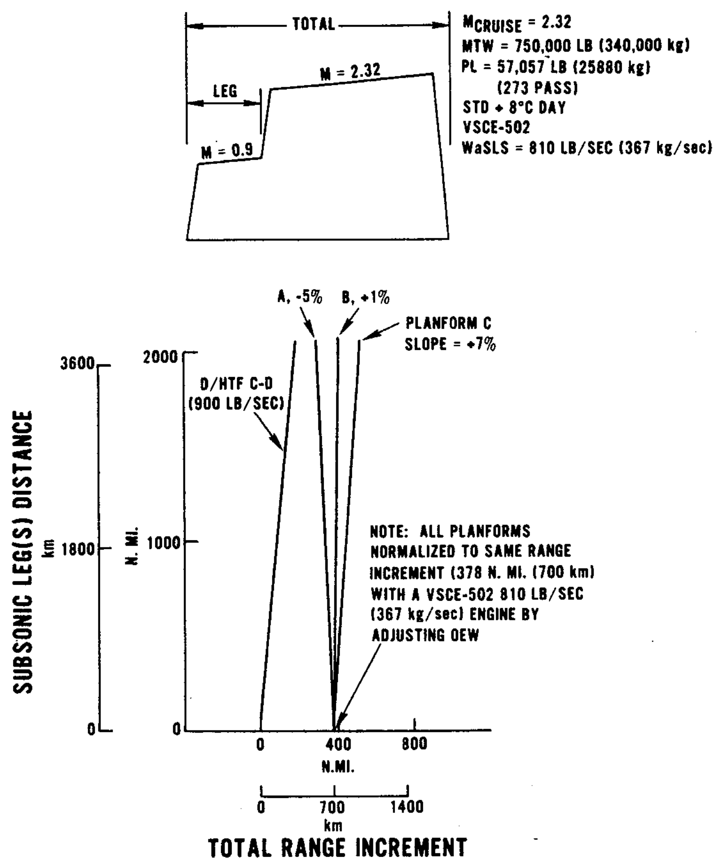


Figure 3.3-11 Effect of Planform on Subsonic Leg Capability

3.3.2.3 Pod Shape and Location

A study was made to determine methods of reducing the wing-nacelle drag of delta wing SST's with VCES. These engines are housed in pods which are somewhat longer than those that were used on the National SST, and their use has resulted in higher wing-pod wave drag at transonic and cruise Mach number. This investigation started by using the baseline airplane configuration and a preliminary Boeing engine pod shape. The engine installation variations considered were:

- Changing the forecowl shape.
- Moving both the inlets simultaneously.
- Moving the inlets separately.

Wing-pod wave drag was calculated using the new NASA integrated design and analysis computer program.

Effect of Forecowl Shape

Variations in forecowl shape were obtained by varying the diameter at the fan flange (approximately 11.5 ft (3.5m) aft of the inlet) for an 810 lb/sec (370 kg/sec) size pod. The inlet stations were held at 179.17 ft (54.6m) from the body nose. The effects of these area changes are summarized at the top of Figure 3.3-12. These data indicate that increasing the local cowl diameter at the fan flange increases cruise and transonic drag, while reducing it has the opposite effect. The data point at $A_1/A_{inlet} = 1.0$ is effectively the same as reducing the pod length, since the diameter from the inlet to the fan flange is constant.

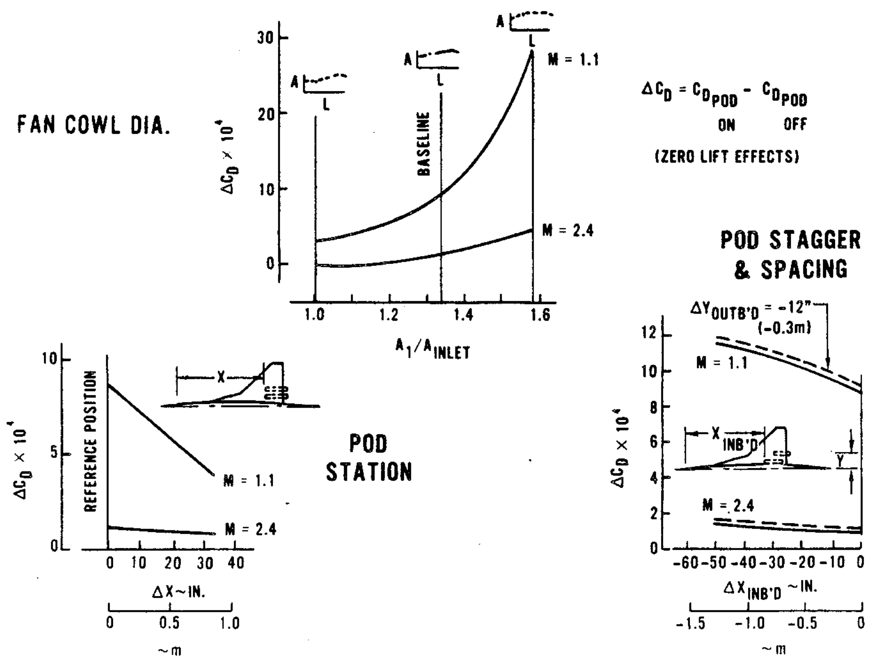


Figure 3.3-12 Pod Drag Sensitivities, MN = 1.1 and 2.4

Effect of Inlet Location

The effect of inlet location was studied by shifting both 810 lb/sec (370 kg/sec) pods 34 inches (0.86m) aft, such that their maximum diameters were coincident with the wing trailing edge. The results are summarized in the lower half of Figure 3.3-12, which indicates a moderate reduction of 5 counts relative to the reference location. The effect of outboard airfoil shape was also studied. The modified double-wedge airfoils outboard of the planform break (WBL 403.7) were replaced by biconvex airfoils with the same depth at the rear spar. The effect of the change in outboard airfoil shape was slight. (Maximum change was +0.6 counts with inlets at 179.17 ft (54.6m.)

Effect of Spacing and Stagger

The influence of pod stagger was calculated by holding the outboard 810 lb/sec (370 kg/sec) size pod at 179.17 ft (54.6m) from the body nose and moving the inboard pod forward parallel to its axis. In addition, the outboard pod was moved inboard 12 in. (0.3m) and the outboard pod was translated forward as in the previous exercise. The results are summarized in Figure 3.3-12, which indicates that forward movement of the inboard pod and inward movement of the outboard pod each result in higher transonic and cruise drag relative to the original inlet positions. The increases in transonic drag are relatively large due to movement of the inboard pod inlet ahead of the wing maximum thickness in that region which is not offset by improved mutual pod interference.

These studies have indicated that the wing-pod drag can be reduced by the following changes:

1. Both pods should be moved aft so that the maximum diameter is coincident with the wing trailing edge.

2. The diameter at the fan flange should be reduced so that the rate of cross-sectional area growth increases to the maximum diameter point.

3. The length of the pod from the inlet to the maximum diameter should be as short as possible.

In addition, the following conclusions can be surmised from these data:

1. The detailed shape of the outboard wing airfoil has relatively little effect on the total wing-nacelle wave drag.

2. Stagger and closer lateral placement of the pods will increase transonic drag.

3. Inlet spillage interference effects from the longer valved VCE pods will likely increase transonic drag because the growing streamtube will pressurize the wing ahead of its maximum thickness.

VSCE-502 and MCE-7 Pod Shape Studies

The VSCE-502 pod shown in Section 3.1.5 is based on a Boeing selected nozzle bend station (at the plane of the bypass stream nozzle hinge line), and a nozzle ejector external cross-section that is elliptical. These choices were made to minimize the pod cross-sectional areas and boattail angles. Two other options were defined, as shown in Figure 3.3-13, which utilize circular nozzle cross sections, and in one case, locates the nozzle bend station at the plane of the rear bearing support. The latter option is preferred by P&WA from a mechanical design standpoint, but has undesirable characteristics from a pod drag and installation consideration.

A further improvement in pod drag could be realized if engine inlet case diameter is reduced. This would pull in the front frame and engine waist diameters. Such a change would also influence the choice of nozzle geometry.

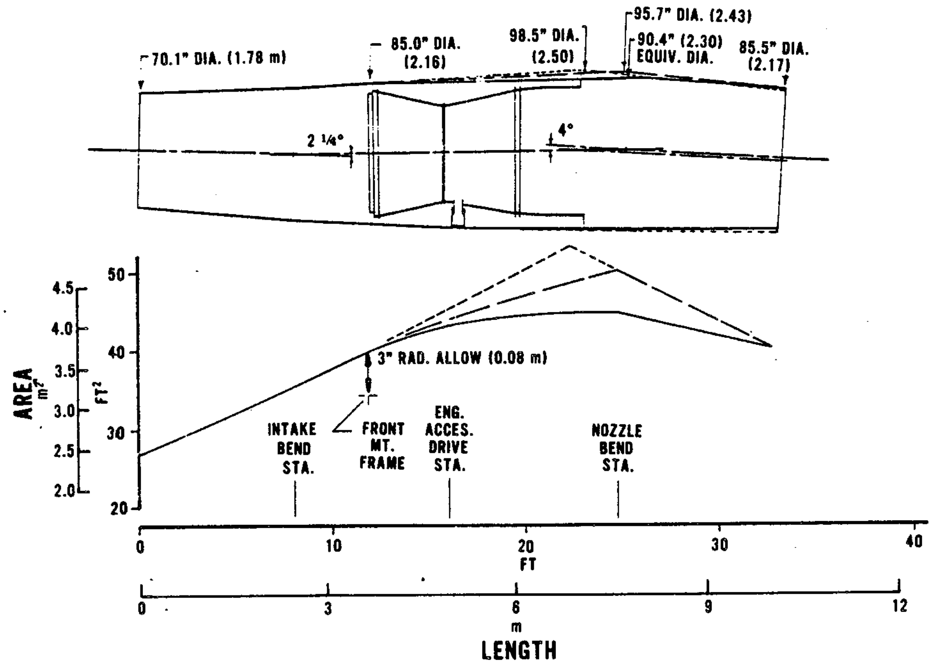


Figure 3.3-13 VSCE-502 Pod Geometry Variations

3.4 DESIGN STUDIES

3.4.1 Conceptual Design of Unique Components

Conceptual design and analysis was conducted in Task VIII for several engine components which are either unique to candidate Variable Cycle Engines or are essential to minimizing pollution and noise or improving economic characteristics of the engines being evaluated.

The conceptual design and analysis work was conducted to establish preliminary feasibility of these unique engine components. Further design refinement was accomplished as part of the preliminary design effort in Task X. More of this design study is required as the field of candidate engines is narrowed. This work elevates the level of definition of the unique components closer to that of the more conventional engine components and improves and substantiates the overall engine definition for these parametric studies. Furthermore, and perhaps most important, this conceptual work identified the advanced technology requirements for these unique components.

The following engine components were identified for conceptual design and analysis in Task VIII and are described in this section of the report:

- Flow Diverter Valves
- Third Turbine Assembly for Dual-Valve and Single Rear-Valve VCES
- Engine Configuration Arrangements
- Nozzle/Reverser/Suppressor Systems

3.4.1.1 Flow Diverter Valves

The flow diverter valve is a totally new engine component. It can be used between two fan assemblies or, in the case of the single rear-valve or dual-valve VCE's, can be incorporated in the rear, higher temperature portion of the engine. The purpose of the flow diverter valve is to invert two flow streams for one mode of operation or, in the opposite position, allow these two streams to pass straight through in the alternate mode of operation.

Three flow diverter valve concepts have been devised which show potential suitability for Variable Cycle Engines. During Phase I of the AST contract, the movable-chute concept (Figure 3.4-1), which lends itself to an auxiliary inlet and nozzle application, was defined and evaluated through several stages of refinement. The second flow diverter valve concept is the Annulus Inverting Valve (AIV), a Boeing concept. As part of a separate P&WA subsonic VCE study, a third scheme, the variable flap concept, was developed.

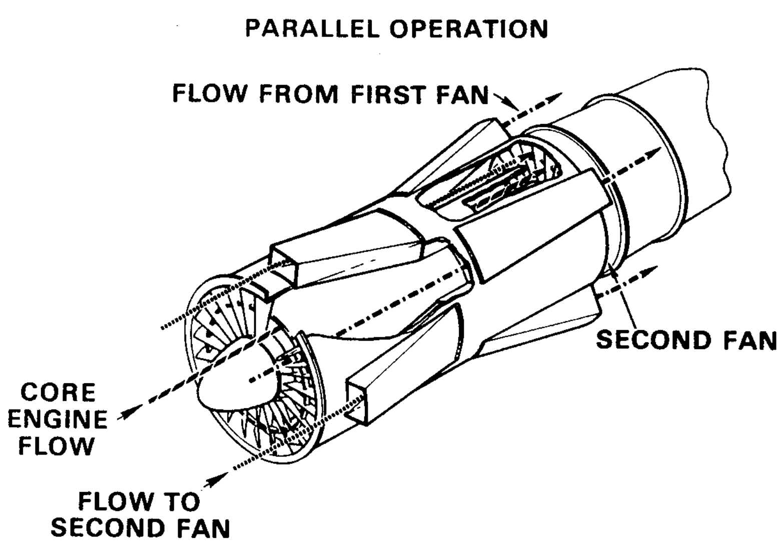


Figure 3.4-1 Series/Parallel Variable Cycle

Since considerable effort was expended during Phase I on the movable-chute concept, the flow diverter valve conceptual design work in the Phase II study concentrated on the AIV and the variable-flap concepts. Furthermore, the AIV and variable flap concepts offer potential length, sealing and aerodynamic improvements over the movable-chute concept. The AIV was used as the baseline definition for the flow diverter valves utilized in all of the VCE parametric and integration studies in Phase II. Conceptual design and analysis was conducted for these valves for both the forward and rear-valve VCE applications.

Forward Flow-Diverter Valve – AIV Concept

The AIV is shown schematically in Figure 3.4-2. As shown, the two flows may be inverted in one mode of operation, or passed straight through in the alternate mode of operation, by indexing half the valve the width of one of the ducts. Indexing involves circumferential rotation of the valve half around the engine centerline.

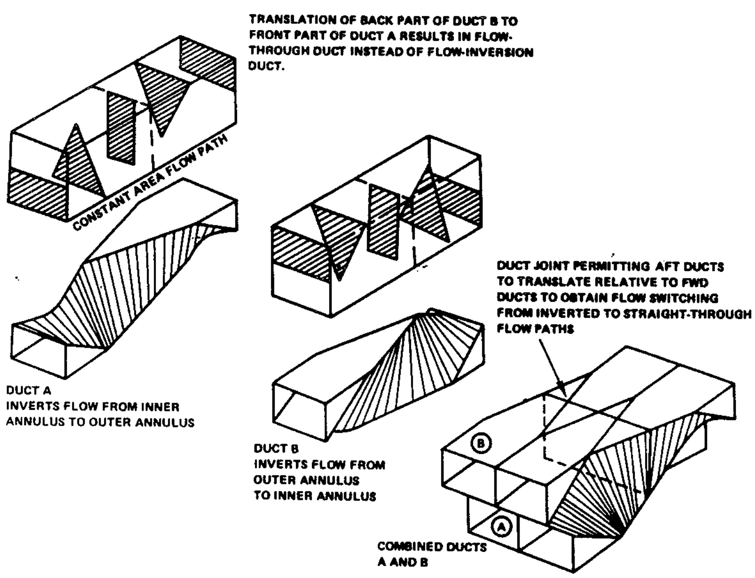


Figure 3.4-2 *Annulus Inverting Valve*

In the forward valve application, the AIV is positioned between two fan assemblies as shown in Figure 3.4-3. In the inverted mode of operation, the walls separating the two airflow paths must be capable of withstanding a total pressure difference of approximately 20 psi (138 kN/m^2). The valve panels must also be designed to avoid the excitations caused by the rotating fan blades upstream and downstream of the valve. The 600°F (320°C) maximum temperature environment existing with a 2.5 fan pressure ratio, Mn 2.4 design, allows a composite material to be used for minimum weight. Based on preliminary fan blade frequency and stress considerations, graphite/polyimide composite material walls with 0.020 in. (0.005m) thick walls was selected.

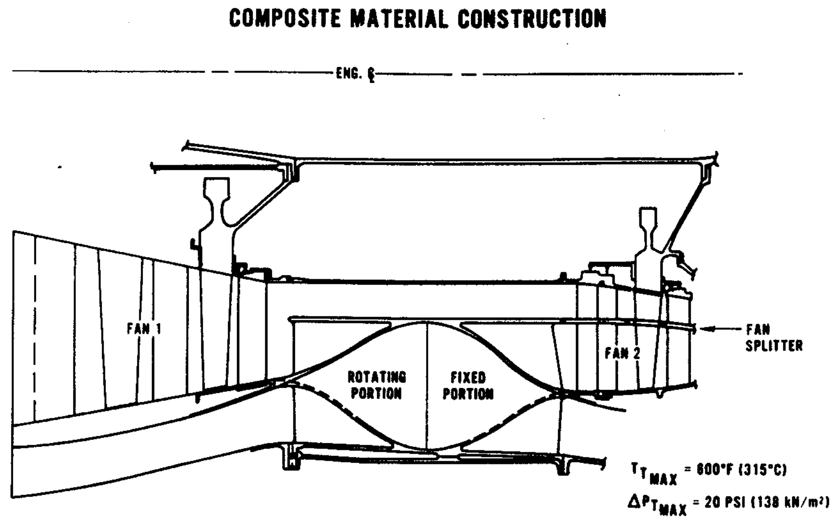


Figure 3.4-3 Forward AIV

The AIV fabrication concept utilizes individual mandrels for each chute around which the composite material is built up. The total number of chutes is assembled and then wrapped with composite reinforcement, thus forming the outer and inner circumferential AIV walls. At this point, the mandrels, which would be collapsible due to the intricate chute shapes, are removed.

As indicated in Figure 3.4-3, the forward half of the AIV was selected as the rotating portion to place engine support struts through the rear fixed portion of the AIV. In this location, the rotor support struts are closer to the high and low spool thrust bearings. A static box structure is constructed around the AIV, as shown, to avoid passing the engine structure through the rotating valve. Actuation can be by means of a "bicycle chain" or a hydraulically controlled bellcrank.

Forward Flow Diverter Valve – Variable-Flap Concept

The variable-flap concept was devised as part of a separate P&WA subsonic VCE study. It was evaluated in the Task VIII design study as an alternative to the Boeing AIV concept.

In this concept, shown schematically in Figure 3.4-4, the two flows are brought from two coannular ducts at the front to two coannular ducts at the back. In contrast to rotating half the valve, as in the AIV concept, flow is controlled between these four annular passages with radial flaps. The flow inversion mode is shown in Figure 3.4-4 by the solid lines, and the alternate mode of passing the flow straight through is shown by the dotted lines.

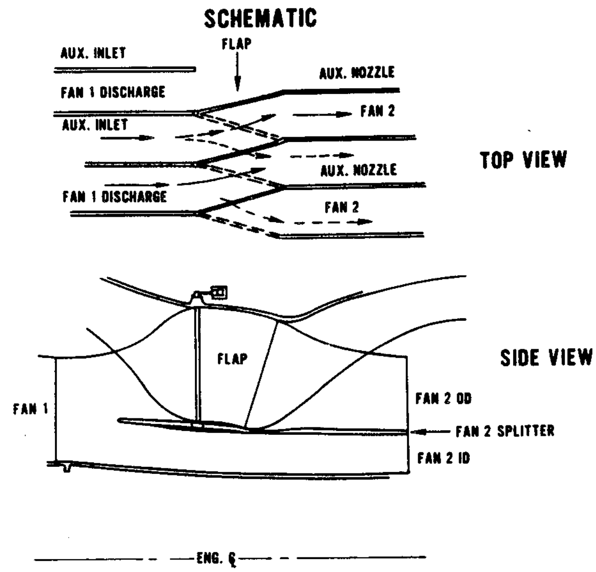


Figure 3.4-4 *Variable Flap Inverter Valve Concept Schematic*

Figure 3.4-5 shows a conceptual design of the variable-flap valve utilized in the forward valve application between two fan assemblies of a VCE. The airflow is routed to either the second fan assembly or to the bypass duct by means of the movable flaps. Fore and aft of these flaps are fixed chutes from the auxiliary inlet and first fan, and to the second fan and bypass duct. A series of spherical surfaces, required at the inner and outer region of each flap, create a complex surface which contributes to fabrication complexity and increased cost. The flap section of the valve also results in an addition of approximately 6.0 inches (0.15m) to the valve length compared to the AIV.

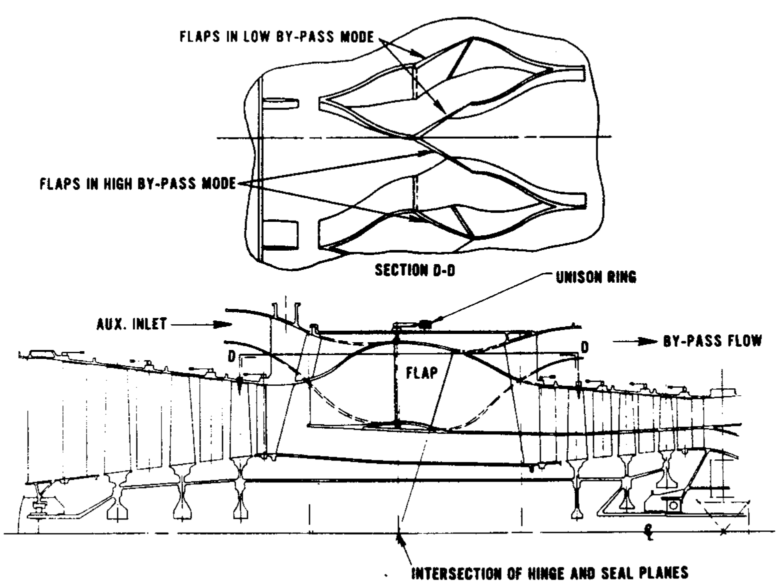


Figure 3.4-5 *Forward Variable Flap Inverter Valve*

A static box structure is shown around the valve, as with the AIV, to pass the engine structure around the valve. However, it is felt that the outer portion of this box structure could possibly be eliminated by passing the engine structure through the non-rotating outer wall. This would produce a more integrated structural design and lighten the valve structure to help offset the increased weight associated with the addition of the flaps.

Compared to the AIV, this concept requires more actuator mechanisms. It also requires sealing at the top and bottom of the flaps in addition to sealing along the radial walls which is a common requirement for both concepts.

Rear Flow Diverter Valve – AIV Concept

Conceptual design and analysis of the AIV in the rear-valve application was also conducted as part of Task VIII. This valve conceptual design work utilized the dual-valve VCE as the base configuration and is shown in Figure 3.4-6.

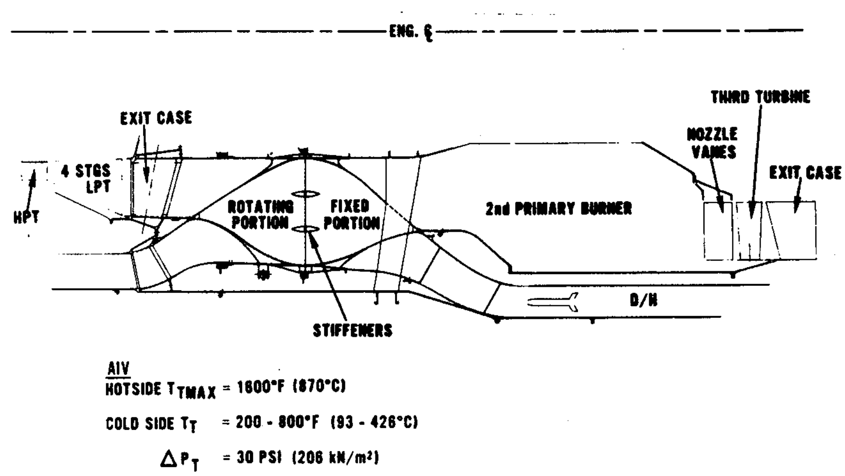


Figure 3.4-6 VCE-Third Turbine/Rear AIV

The rear-valve is required for the dual-valve VCES to invert the two airflow paths between the two low-pressure turbine assemblies. The rear-valve is exposed to a much higher temperature environment than the forward valve, with the maximum gas temperature of approximately 1600°F (870°C) passing through the valve. The temperature difference between the two airflow streams varies from 800 to 1400°F (430 to 760°C) thus producing severe thermal conditions on the valve. In addition, this temperature gradient is reversed as the valve is rotated. The walls must be capable of withstanding a total pressure difference between the two airflows of approximately 30 psi (607 kN/m^2) at these elevated temperatures. Preliminary structural estimates of the rear valve indicate advanced nickel base superalloy walls approximately 0.060 inch (0.0015m) thick may be adequate without cooling if two circumferential stiffening rings are attached to the mid-portion of the valve. The combined cool side and hot side result in a metal temperature low enough to not require cooling, but precludes the use of lighter, honeycomb construction due to its thermal resistivity.

A static box structure is constructed around the rear AIV to isolate the rotating portion of the valve from the engine structure. This is especially critical for the rear AIV with its more severe thermal requirements. A sheet-spring design has been incorporated to absorb the thermal loads and to isolate them from the static support structure of the engine.

Comparison of Valve Concepts

Table 3.4-I compares the variable-flap concept to the AIV concept.

TABLE 3.4-I

FLOW-DIVERTER VALVE COMPARISON
VARIABLE-FLAP CONCEPT RELATIVE TO AIV

Pros

Similar Aerodynamics

More Integrated Structure

Mixed Flow Capability

Cons

Fabrication Complexity – Cost

More Difficult Sealing

More Actuation

Slightly Increased Weight – (0.2% Engine + Nozzle)

Longer Length – (2% Engine + Nozzle)

Needs Fail-Safe Design

The variable-flap valve concept utilizes existing variable fan/compressor stator technology with similar aerodynamic characteristics relative to the AIV concept. However, this concept increases the fabrication complexity due to more complex surfaces, more difficult sealing because of these complex surfaces and because of additional areas requiring sealing, and more actuation mechanisms. The variable-flap valve concept is also slightly heavier and longer than the AIV concept. This slight weight difference includes elimination of a portion of the box structure around the variable-flap valve, as discussed previously.

By moving the flap hinge line to the flap trailing edge, the variable-flap valve concept can provide the additional capability to divert two streams into one stream. This mixed flow is accomplished by actuating every other flap. By actuating the flaps to an intermediate position, a partial mix of the flows can be accomplished which has the advantage of permitting airflow matching into the third turbine, for a rear-valve VCE application, as the second burner is turned off and on between subsonic and supersonic cruise, respectively.

This comparison shows that for the purposes of parametric systems studies of various engine configurations conducted in Tasks VII and XIII, either the AIV or variable-flap valve concept could have been selected as the baseline flow diverter valve definition. For all of the front-valve VCE concepts, the AIV was selected, primarily because of its weight and length advantages over the flap or chute valve concepts. For the dual-valve VCE's, the AIV was selected for the rear valve because of the same advantages. With the evolution of the single rear-valve VCE concept, the unique capability of the flap concept to mix the two streams and thereby improve performance when the duct-burner is not lit, resulted in the selection of the variable-flap flow diverter valve for the refined studies of the rear-valve VCE concept.

3.4.1.2 Third Turbine Assembly for Valved VCE Concepts

Because of the large corrected airflows associated with the third turbine (Figure 3.4-6), an extremely large annulus area is required. Consequently, the third turbine is the component which sets the low spool rotor speed. To minimize the penalty of lower speeds on the remainder of the low-spool engine components, this rear turbine is required to operate at very high blade stresses. In addition, this turbine experiences high inlet temperatures, because of the second burner, and its environment is therefore comparable to a high-pressure turbine design. To maximize the low-rotor speed, an advanced high-stress third turbine design with an internal cooling system is required. This includes more severe tapering of the blade root-to-tip chord and root-to-tip wall thicknesses. A high exit Mach number from this turbine helps to reduce the blade annulus area. An advanced directionally solidified eutectic blade material is required to withstand these high stresses and temperatures.

A possible alternative approach to the design of these dual-valve VCE concepts is a three-spool configuration. This reduces the number of other engine components that are penalized because of the lower rotor speeds dictated by the third-turbine design. Most of the dual-valve VCE's, however, are operated such that the third-turbine work output varies considerably as the second primary burner is turned on and off at the supersonic and subsonic conditions, respectively. This is one of the flexibilities of the dual-valve VCE; the capability to transfer the required fan work back and forth between the gas generator low-pressure turbine and the third turbine, as the third-turbine inlet temperature is varied over a wide range. A triple spool design would prevent this low-spool variable turbine work split capability, and force the third turbine to extract large amounts of work at low turbine inlet temperatures (subsonic cruise) with a corresponding detrimental effect on the overall thermodynamic cycle.

Advanced fabrication technology would be needed to produce these large turbine blades from directionally solidified eutectic material with an advanced cooling scheme. Some of the VCE configurations operate this third turbine over wide ranges of turbine inlet and exit airflows and may require variable inlet-guide-vanes and/or variable exit-guide-vanes to achieve the desired engine matching characteristics and to minimize exit-guide-vane losses.

3.4.1.3 Engine Arrangements

A number of different engine configurations were evaluated in the Task VII and XIII systems studies including LBE's, VSCE's, single-valve VCE's and dual-valve VCE's. Conceptual design work was conducted to establish the engine configuration feasibility and improve the engine configuration definition utilized in these systems studies.

Low Bypass Engine (LBE)

The LBE designs (0.1 to 0.5 BPR) were configured as mixed-flow single-spool engines with and without an afterburner. Results indicated a non-afterburning configuration with a 0.1 BPR (LBE-405B) is best on an overall TOGW versus noise comparison. A conceptual configuration for the LBE-405B is shown in Figure 3.4-7.

For the 0.1 BPR engine, a manifold and six-pipe bypass system is used for the bypass airflow, instead of an annular duct, to minimize the pressure loss and weight of the bypass system. The choice of a single spool configuration was made for the parametric study. Further detailed engine design and performance studies of a one versus two-spool arrangement are required before a final configuration is selected. The single spool was configured with three bearings, two roller bearings and one thrust bearing located at the intermediate case, as shown. The engine mounts were located at the turbine case and the low-pressure compressor inlet-guide-vane; the inlet case provides the thrust mount.

One of the advanced technologies that has special significance for this family of LBE's is the high-strength turbine blade material. This advanced material enables the rotors to be designed for high speeds, thereby reducing the number of compressor stages required to provide the design pressure-ratio. A further improvement resulting from higher rotor speeds is a reduced turbine elevation with no compromise to efficiency. These changes are especially significant to weight and dimensional characteristics of these LBE's because of their large gas generator size.

As indicated in Figure 3.4-7, a tube jet-noise suppressor was evaluated for these LBE's and is another critical component because of high jet-velocities.

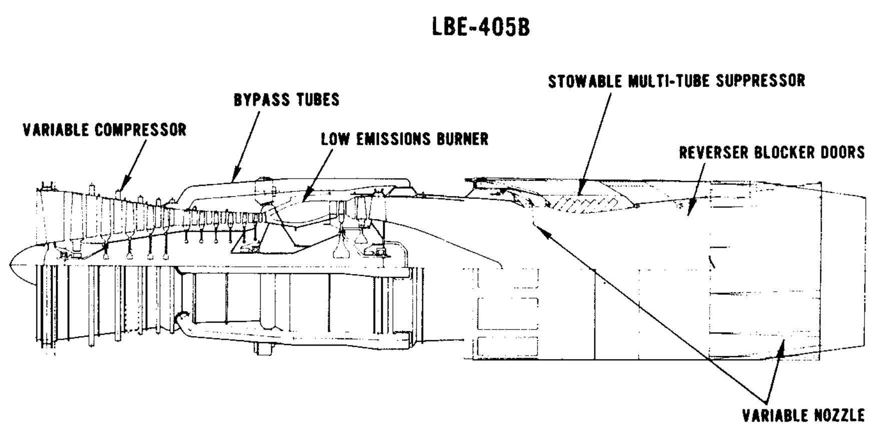


Figure 3.4-7 Low Bypass Engine, LBE-405B

Variable Stream Control Engine (VSCE)

Figure 3.4-8 shows the conceptual arrangement for the VSCE. This engine has an intermediate BPR (~1.3) and incorporates the inverse throttle schedule discussed in Section 3.2.1.2. Extensive use of variable geometry is employed, including variable fan-inlet and exit-guide-vanes, variable compressor stators, possibly variable turbine exit-guide-vanes, variable primary nozzle area, variable fan-duct nozzle area, variable nozzle-exit area, a thrust reverser and possibly a stowable jet-noise suppressor in the bypass stream as a back-up to the coannular noise benefit. In addition, a low-emissions low-temperature duct burner is required, as well as a low-emissions primary burner with inverse throttle schedule.

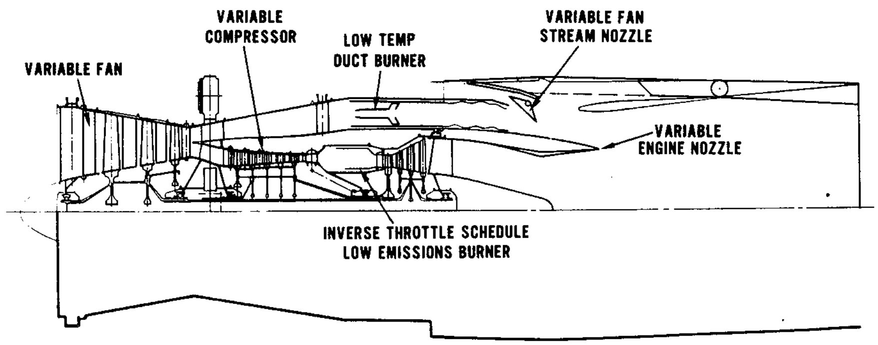


Figure 3.4-8 Variable Stream Control Engine, VSCE-502

The advanced technology material definition is the same as that evaluated for the valved VCE's and the LBE's, and includes the use of composite fan blades, ceramic turbine inlet-guide-vanes with minimum cooling, and advanced directionally solidified eutectic turbine blades. The high strength turbine blade material enables the rotors of both spools to be designed for high speeds, thereby minimizing the number of fan, compressor, and turbine stages.

The engine is configured with two spools supported by five bearings, as shown. The thrust bearing for each spool is located at the intermediate case.

A two-mount engine support system has been devised by passing the rear engine structure across the bypass stream, just ahead of the duct-burner, to the rear mount. The fan duct would be split to allow access to the primary burner and high-pressure compressor for engine maintenance. In addition, access to the turbines will require the duct-burner liners to be split or to slide rearward.

Single-Front-Valve Variable Cycle Engine

The conceptual cross-section in Figure 3.4-9 depicts the major components that constitute a representative single-front-valve VCE. The basic gas generator and low-pressure turbine are direct derivatives from the VSCE with the same levels of advanced technology. The unique component is the annulus inverting valve (AIV) located between the two fan assemblies. This engine concept has the capability of reducing BPR from a medium level for take-off to a low level for supersonic operation, as described in Section 3.2.1.2.

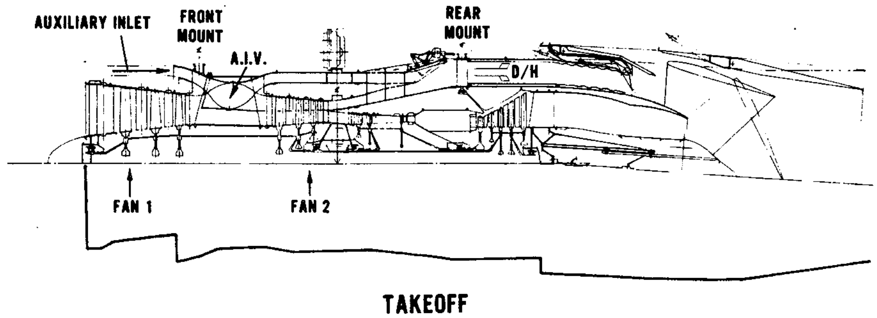


Figure 3.4-9 *Front Single Valve Variable Cycle Engine, VCE-107*

In this configuration, the two bypass streams are mixed into one common stream which has an augmentor. This arrangement avoids the necessity for an auxiliary nozzle system for the outer bypass stream. A valve is required at the juncture of the two streams to shut off the outer duct when the two fan assemblies are in series (low bypass mode) operation. The engine is configured with two spools supported by five bearings. The thrust bearing for each spool is located at the intermediate case. As with the VSCE, the rear engine structure is passed across the bypass stream, just ahead of the duct-burner, to the rear mount. A static box structure is designed around the AIV to route the engine structure around the rotating portion of the valve to the front mount. This design is required for structural integrity, but is a factor that contributes to the high VCE weights. The second fan assembly requires a rotating flow splitter to prevent the supercharged gas generator airflow from leaking into the auxiliary inlet airflow into the second fan when the engine generates in the high bypass mode.

Dual-Valve Variable Cycle Engine

The conceptual cross-section in Figure 3.4-10 shows the component arrangement for a representative dual-valve VCE. This engine has the capability of converting to two turbojet cycles for supersonic operation, as described in Section 3.1.1.

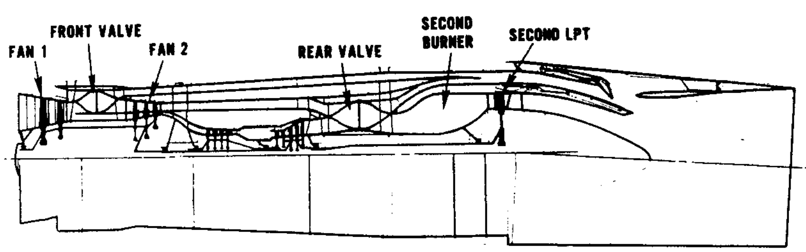


Figure 3.4-10 *Nonaugmented 2 Nozzle Stream Dual Valve VCE*

The use of the second burner at take-off eliminates the need for an augmentor in this configuration. The two bypass streams are mixed into one common stream, thereby avoiding the necessity for an auxiliary nozzle system for the outer bypass stream. The engine is configured with two spools supported by six bearings. The additional bearing, compared to the previous two engine configurations, is required for the additional low-pressure turbine. A static box structure is designed around each of the AIV's to route the engine structure around the rotating portion of the valve. This is required for structural integrity, particularly in the case of the rear AIV with its more severe thermal requirements. A two-mount engine support system is shown with the rear turbine assembly overhung on an extended low spool shaft. The second fan assembly requires a rotating flow splitter as is the case with partial-span forward AIV's. The advanced high-strength turbine blade material is required for the rear turbine to maximize the allowable low-rotor speed and thereby reduce the number of fan 1, fan 2, LPT and rear turbine stages and elevations. The two fans employ variable geometry stators to provide the higher airflow schedule described in Section 3.1.3.1.

3.4.1.4 Nozzle/Reverser/Suppressor Systems

The nozzle/reverser/suppressor (N/R/S) system is perhaps the most critical engine component in terms of its impact on the total airplane system. The requirements for the N/R/S are complex and indicate the need for a highly integrated design. These requirements must be met with minimum penalty to engine installation, reliability and performance.

A high area-ratio convergent-divergent nozzle is required for good supersonic cruise performance while at take-off and subsonic cruise conditions, an essentially convergent nozzle configuration is required. To match the inlet airflow schedule and accommodate varying degrees of duct-burning, variable nozzle throat and exit areas are required. Effective thrust reversal of both the primary and bypass streams is an assumed requirement for advanced commercial airplanes. Should this requirement be modified in the future, the nozzle system complexity will be greatly reduced.

At the outset of the Phase II study, the coannular noise benefit had not been substantiated. It was therefore assumed that jet noise suppressors were essential to environmentally acceptable AST engines. By designing the VSCE and valved VCE concepts for proper selection of fan pressure ratio (FPR), combustor exit temperature (CET) and bypass ratio (BPR), the jet velocity of the primary exhaust stream can be reduced so that this stream does not contribute to the total jet noise; and therefore a jet noise suppressor would be required in the bypass stream only. Suppressor configurations for VSCE's and valved VCE's would then be facilitated, relative to LBE's, due to the favorable height-to-length geometry of the bypass stream. The performance penalty associated with all noise suppressors requires that these devices be stowable after take-off.

As the Phase II study progressed, the coannular noise benefit was substantiated by static model tests. Because both the VSCE and valved VCE definitions have coannular flows, they may all benefit from the noise suppression characteristics of coannular nozzles. If these coannular noise benefits can be confirmed by relative velocity tests and under actual flight conditions, the requirement for stowable jet-noise suppressors may be eliminated.

Several NRS concepts were evaluated in Task VIII for both the VSCE and valved VCE with separate stream, coannular nozzles. Four of the more attractive concepts are reviewed in this report along with the results of preliminary analysis of these systems. The illustrations shown are based on the VSCE configuration.

N/R/S Concept No. 1

Figure 3.4-11 shows the first N/R/S concept configured for take-off. In this concept, a set of fingers is deployed across the bypass stream to break up the bypass stream and promote mixing with auxiliary air which enters through ejector doors. The resulting mixed-jet velocity, which is lower than the non-mixed bypass jet velocity, results in decreased jet noise. When the fingers are deployed, the bypass stream nozzle is retracted and the flow area between the fingers becomes the nozzle throat. A set of internal clam-shell blocker doors, which are used during reverse, are tilted slightly at take-off to aerodynamically line up with the streamlines of the entering auxiliary airflow. The nozzle exit consists of an outer shroud with free-floating tailfeathers. These allow variations in the nozzle exit area depending on the nozzle expansion ratio. The nozzle walls are lined with 1-2 inch (0.025-0.050m) deep acoustic treatment to absorb the higher frequency noise generated by the mixing process. A variable primary-stream throat area is also included in this system.

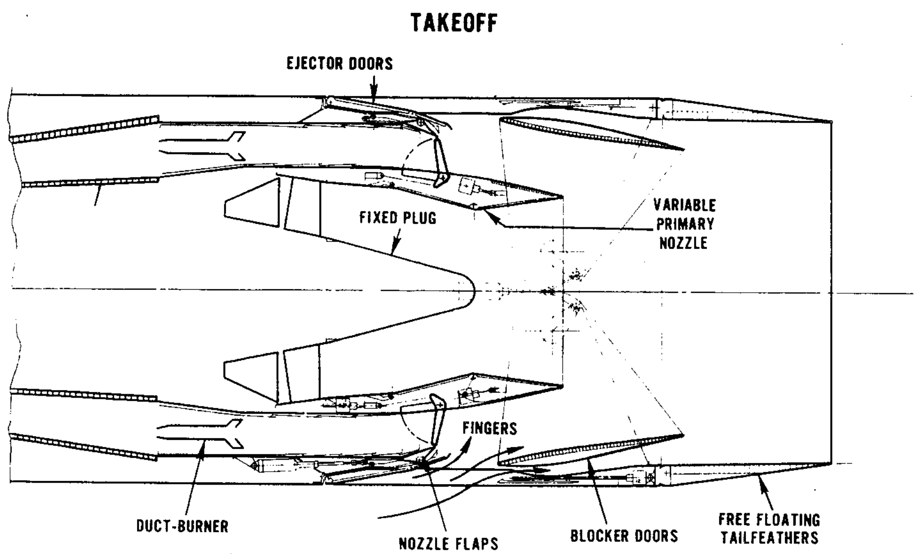


Figure 3.4-11 N/R/S Concept No. 1

The finger-type noise suppressor is a relatively simple device which lends itself to incorporation into the nozzle system with limited impact on the other nozzle system components. The coannular nozzle noise benefit may eliminate the requirement for a mechanical mixer for noise suppression. The finger-type suppressor shown in Figure 3.4-11 would be removed and this configuration would still be an appropriate nozzle concept for the most promising VSCE and valved engine concepts. While the finger-type suppressor is light weight and relatively simple, it is a very abrupt mixing device which results in high thrust-losses at take-off.

Figure 3.4-12 shows the No. 1 N/R/S concept in the subsonic cruise, supersonic cruise and reverse thrust modes of operation. The finger jet-noise suppressors are stowed in the primary nozzle wall and the bypass stream nozzle flaps are set for the required throat area.

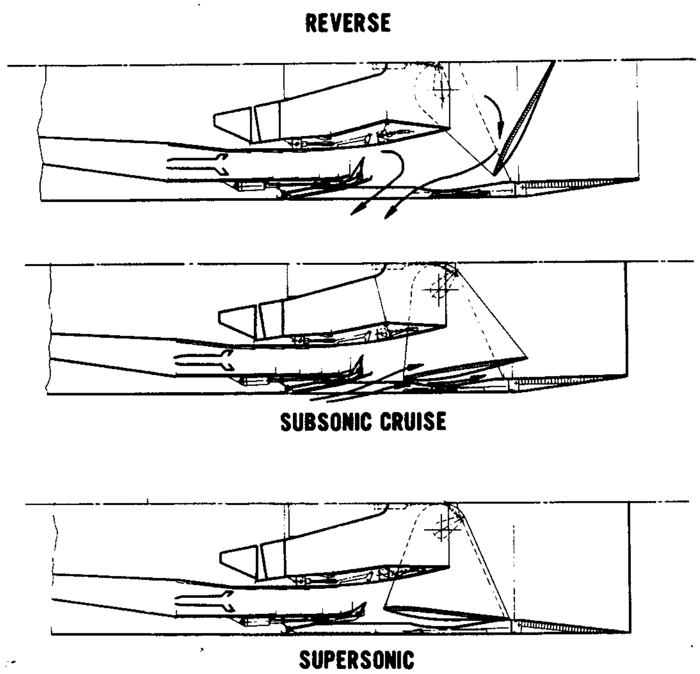


Figure 3.4-12 N/R/S Concept No. 1

At subsonic cruise, the ejector doors allow auxiliary air to enter and fill part of the nozzle exit area which prevents the two engine exhaust streams from overexpanding for this low nozzle-expansion-ratio condition. At supersonic cruise, the ejector doors are shut and the clam-shell buckets form a portion of the nozzle outer wall divergent section. In this mode, the configuration is a high area-ratio convergent-divergent nozzle which is required for good performance at this high nozzle-expansion ratio condition. This concept achieves good nozzle performance at both the subsonic and supersonic cruise conditions.

During the reverse-thrust mode of operation, the ejector doors and a set of translating panels provide the opening for reversing the nozzle airflow. The internal clam-shell buckets are fully closed, providing effective reverse thrust for both nozzle streams and have the capability of targeting the reverse airflow away from adjacent engines and from the runway. This targetability of the reversed airflow is considered a basic requirement because of the engine installation relative to re-ingestion problems, the aircraft wing and fuselage, and problems from runway debris.

N/R/S Concept No. 2

This concept, shown in Figure 3.4-13 in the take-off configuration, is similar to Concept No. 1 except that the large clam-shell buckets form the entire aft nozzle section, thus eliminating the need for a nozzle shroud and tail feathers. This, along with the finger-type suppressor, results in the least complex and potentially lightest weight concept. As with Concept No. 1, a high thrust loss at take-off results from the abrupt mixing of the finger mixers. This would also be an appropriate concept for the coannular noise benefit with the finger-type mixers removed.

For take-off, the clam-shell buckets are slightly tilted, which, in conjunction with a translated external shroud, permit auxiliary air to enter and mix with the bypass stream which has been broken up with the deployed fingers. The tilted position of the clam-shell buckets also reduces the nozzle exit area at this low nozzle-expansion-ratio condition. Since the clam-shell buckets do not provide a planar nozzle exit area, sideplates must be incorporated for good performance.

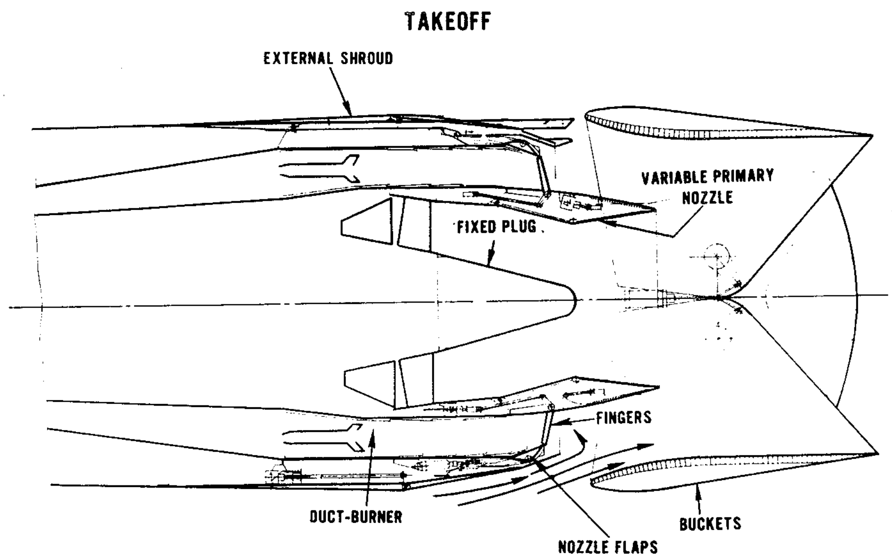


Figure 3.4-13 N/R/S Concept No. 2

For the cruise conditions, the fingers are stowed in the outer wall of the primary nozzle, and the fan-duct nozzle flaps are set at the required throat area. At subsonic cruise, the circular external shroud is translated forward and the clam-shell buckets tilted to allow auxiliary air to fill part of the nozzle exit area. However, the tilted clam-shell buckets do not provide a fully circumferential ejector opening which results in local deficiencies in area for the ejector airflow. At supersonic cruise conditions, the external shroud is in the closed position. The clam-shell buckets form the divergent portion of the nozzle which is required for good performance at this high nozzle-expansion-ratio condition.

Targeted reverse thrust is obtained by fully closing the clam-shell buckets and translating the external shroud forward to provide the exit area for the reversing nozzle streams. The effectiveness of this reverser is estimated to be marginal and some better means of facilitating the turning and reversing the flow will be required, such as cascades in the ejector openings.

N/R/S Concept No. 3

This concept, shown in Figure 3.4-14 in the take-off position, consists of a chute mixer for jet-noise suppression, internal clam-shell buckets and a nozzle shroud with free-foating tailfeathers. An external circular shroud is translated forward to allow auxiliary air to enter through every other chute (cold chutes) and mix with the bypass stream which passes through the alternate chutes (hot chutes). Sidewalls separate the two flows. The nozzle exit consists of an outer shroud with free-floating tailfeathers. A variable primary-stream throat area is obtained by a translating-flap (iris) nozzle. The chute mixers, which penetrate completely across the bypass stream, bring the bypass stream and auxiliary air together in a less turbulent manner than the finger-type mixer concept; therefore, the chutes result in lower thrust loss when deployed.

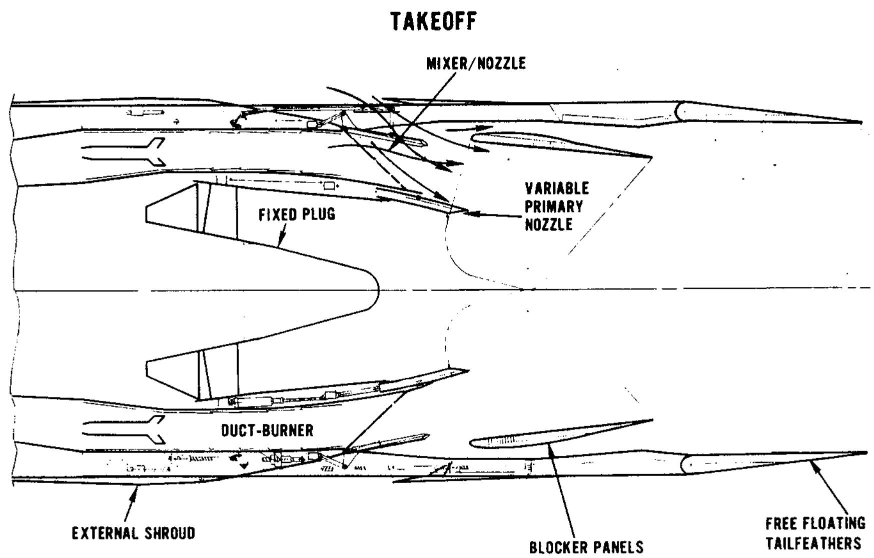


Figure 3.4-14 N/R/S Concept No. 3

At the cruise conditions, the outboard ramp of the "hot" chutes is pulled inboard to join with the inboard ramps of the "cold" chutes to form a complete annular flap. This becomes the bypass stream throat and is set at the required area by rotating this nozzle flap away from the fully penetrated position. Consequently, stowing of the chute mixers and a separate nozzle-flap system are not required for the bypass stream. At subsonic cruise, the circular external shroud is translated forward to allow auxiliary air to enter and fill part of the nozzle exit area. The auxiliary airflow scrubs the chute sidewalls resulting in a moderate nozzle performance loss at subsonic cruise. At supersonic cruise conditions, the external shroud is in the closed position and the internal clam-shell buckets form a portion of the divergent nozzle section. The chute sidewalls are located behind the nozzle flaps, out of the bypass stream airflow, and therefore do not impose a loss in nozzle performance.

Effective targeted reverse thrust is obtained by fully closing the clam-shell buckets and translating two circular external shrouds forward to provide the exit area for the reversing nozzle streams. Greater exit area is needed for reverse than for the auxiliary airflow entrance at take-off in all of these schemes because of the approximately 50% targeting requirement of the reverse flow. In the integration evaluation, it was determined that translation of the external shrouds may compromise the pod geometry too severely. This concept may be rejected for this reason.

N/R/S Concept No. 4

The tube suppressor, which was also evaluated in the Phase I study, is incorporated in Concept No. 4 along with internal clam-shell buckets and a nozzle shroud with free-floating tailfeathers. This concept is shown in Figure 3.4-15 in the take-off configuration.

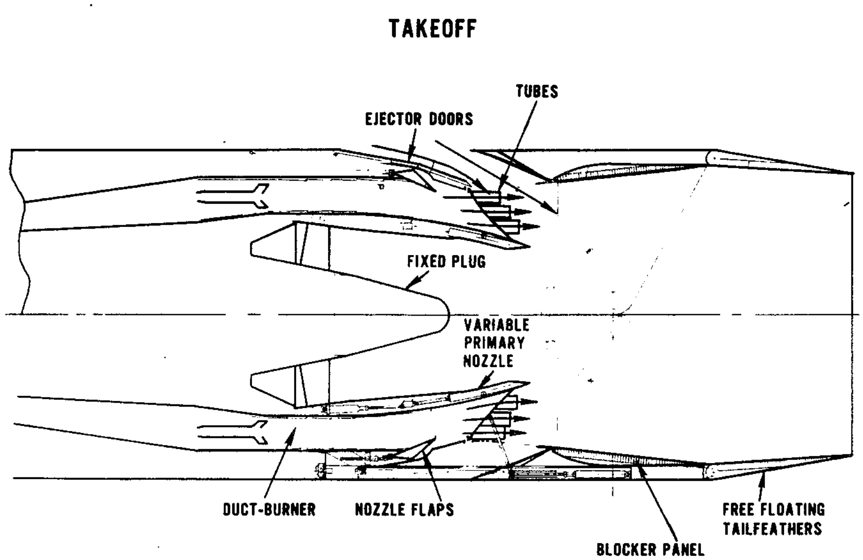


Figure 3.4-15 N/R/S Concept No. 4

The fan-duct airflow passes through the deployed tube suppressors which break up this flow and mixes it with the auxiliary air which enters through a series of ejector doors. When the tube segments are deployed, the bypass stream nozzle flaps are fully retracted and the flow area of the tubes becomes the bypass stream throat. The nozzle exit consists of an outer shroud with free-floating tailfeathers which allow variation in the nozzle exit area depending on the nozzle expansion ratio. For cruise, the tubes are stowed in the outer nozzle wall, and the bypass stream nozzle flaps provide the required throat area. At subsonic cruise, the aft portion of the nozzle is translated aft to permit ejector airflow to fill part of the nozzle exit area. The stowed tubes block the blow-in door passage, thus necessitating translating the aft portion of the nozzle. A substantial nozzle performance penalty is incurred at subsonic cruise as a result of the bypass stream overexpanding before the entrance of the ejector airflow. This is caused by the axial displacement between the throat formed by the nozzle flap and the ejector airflow. At supersonic cruise, the nozzle shroud is translated closed. In this mode, the high area-ratio convergent-divergent nozzle provides good performance for the high nozzle-expansion ratio.

Effective, targeted, reverse thrust is obtained by fully closing the internal clam-shell buckets and translating the aft nozzle shroud to provide the exit area for the reversing nozzle streams. Aft translation of the clam-shell buckets is also required in this scheme. This requirement contributes to the complexity and weight of this concept.

Tube suppressors have been demonstrated to provide slightly more noise suppression capability than the previous concepts. The thrust loss for this device when deployed is almost as high as finger mixers. The tube concept is more difficult to stow, it has larger weight and dimension penalties and also presents a discontinuous surface (holes) to the expanding air in the stowed mode, resulting in a small performance penalty.

Comparison of Nozzle Concepts

Preliminary evaluation of the various N/R/S concepts was conducted for the VSCE-502 configuration. The results are shown in Table 3.4-II. The chute concept (No. 3) was selected as the base for this relative comparison because of its low suppressor-thrust-loss.

TABLE 3.4-II

N/R/S SUMMARY COMPARISON

VSCE-502

N/R/S CONCEPT	1	2	3	4
DESCRIPTION				
• SUPPRESSOR	FINGERS	FINGERS	CHUTES	TUBES
• NOZZLE EXIT	TAILFEATHERS	CLAMSHELL	TAILFEATHERS	TAILFEATHERS
WEIGHTS				
• RELATIVE (ENG + N/R/S) ~ %	−4%	−8	0	+4
PRICE				
• RELATIVE (ENG + N/R/S) ~ %	−3%	−4	0	−1
NOISE SUPPRESSION				
• ΔPNdB - MAX	13.5 ⟶			15
PERFORMANCE				
• TAKEOFF -ΔCF ~ %	−10%	−10	−4	−7
• SUBSONIC CR ~ ΔTSFC - %	−3%	+7	0	+5
• SUPERSONIC CR ~ ΔTSFC - %	−2%	−1	0	0
• REVERSER EFFECTIVENESS	ADEQUATE	POOR	ADEQUATE	ADEQUATE
RELIABILITY	AVERAGE	BEST	AVERAGE	WORST

The weight and price comparisons show that the relative integration simplicity of the finger suppressors result in nozzle concepts that produce improved (lighter and lower price) N/R/S systems.

Based on DOT-SST static scale model jet-noise suppressor test results, the jet-noise suppression characteristics of the various configurations were estimated as a function of relative jet velocity. Based on these data, the tube suppressor offers slightly more jet-noise reduction.

Nozzle performance of the four configurations is compared in Table 3.4-II for take-off, subsonic cruise and supersonic cruise operation. The thrust losses at take-off are due to the deployed jet noise suppressors, with the finger mixers causing the highest loss. Subsonic and supersonic performance are compared on the basis of TSFC. Concept No. 1 shows the best performance at both subsonic and supersonic conditions. The higher subsonic TSFC's for Concepts No. 3 and No. 4 result from aerodynamic interference with the ejector operation when the jet noise suppressors are stowed, while the high TSFC for Concept No. 2 is due to a deficiency in circumferential ejector area caused by the unsymetrical clam-shell buckets. Supersonic cruise performance differences are due to the following effects: poor internal nozzle aerodynamic wall contours caused by the stowed suppressor, as in concept 4; external drag created by translating shrouds, as in concepts 2 and 3; and a non-planar exit area, as in concept 2. All of the concepts have a small supersonic cruise performance penalty due to the acoustic treatment lining the nozzle walls.

A preliminary reliability comparison indicates concept No. 2 results in the best reliability rating due to fewer and less complex systems and fewer actuators. Concept No. 4, on the other hand, has the most translation, rotation and more complicated systems and therefore is considered to be the least reliable of the N/R/S concepts. The "average" rating indicates average for the four N/R/S concepts evaluated in this study and not average for nozzle systems in current commercial operation.

Figure 3.4-16 shows the impact of the weight, price, suppression and nozzle performance differences, shown in Table 3.4-II, on the vehicle system performance and economics. These results are shown at the same level of augmentation (a 2200 ft/sec (671m/sec) relative jet velocity) and therefore correspond to approximately equal sideline jet noise for each concept.

These vehicle system results show concepts 1, 2 and 3 to be within 2 percent of each other. The relative simplicity of integrating the finger suppressor into the nozzle design has the least impact on weight, price and nozzle performance for the subsonic and supersonic cruise conditions. Therefore, concepts Nos. 1 and 2 are able to offset the disadvantage of the high take-off thrust loss associated with these suppressors in systems that are competitive with the low, thrust-loss chute concept (No. 3). The large clam-shell bucket concept (No. 2) offers further weight and price advantages, and good reliability (which is not quantitatively accounted for in the economic analysis), and would be a more attractive concept if methods of improving its reverser effectiveness and performance could be found. The tube suppressor concept (No. 4) has relatively poor vehicle system performance and economics due to its complexity and consequential impact on weight, price and nozzle performance. As

Figure 3.4-16 shows, concept No. 1 is the most attractive of the concepts evaluated. It should be noted that small changes in ROI are significant, as evidenced by the 3 percent cruise TSFC improvement that would be needed to affect a 1% change in ROI.

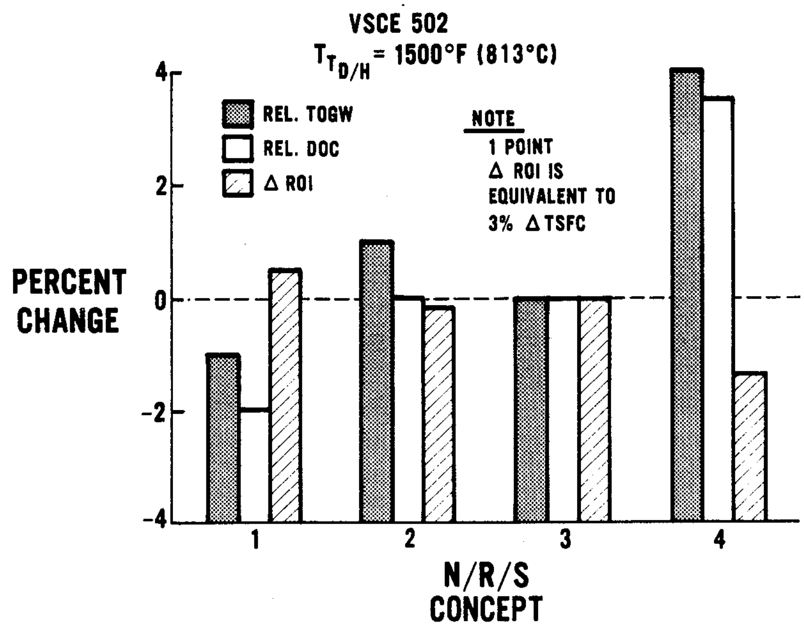


Figure 3.4-16 N/R/S Results Summary

N/R/S Conclusions

Several candidate N/R/S systems were defined in this study. The best of these, accounting for the impact on weight, price, noise reduction, and nozzle performance, offers significant potential vehicle system improvements relative to unsuppressed systems with the engines oversized and throttled back to meet the same noise levels. These system improvements equate to about 15% reduction in TOGW, at constant noise level, or 8 PNdB reduction in noise level, at constant TOGW. However, the results of the coannular noise test program indicate that a mechanical suppressor may not be required and, therefore, a greater potential system improvement may be realized. It is not expected that the amount of suppression assumed for these suppressor concepts would be possible in addition to the coannular benefit. Since effective mixing is already being accomplished, by virtue of the coannular mixing effect, the addition of mechanical mixing devices may not offer a significant further reduction in jet noise. Consequently, the requirement for a jet-noise suppressor depends on further coannular tests with relative velocity and full scale effects.

If it is eventually determined that a jet noise suppressor is required, the final choice of suppressor configuration (i.e., fingers, chutes, tubes, etc.) will depend on in-flight suppressor test results. In this study, the relative integration simplicity of the finger suppressor in the nozzle design resulted in the least impact on weight, price and cruise nozzle performance of the various suppressor types considered. This was able to offset the relatively high take-off thrust loss estimated for the finger-mixers and produce the best overall system results. The chute mixer with improved take-off thrust loss but with a greater impact on weight, price and cruise performance, is also considered to be a possible suppressor concept. The tube suppressor appears to be the most complex of the suppressor types considered, and consequently results in the greatest impact on weight, price, reliability and cruise nozzle performance and it does not appear attractive for coannular nozzles. The final choice will depend on the coannular noise benefit and on whether further suppressor tests show the same suppression and thrust-loss characteristics used for this study. All of these N/R/S concepts are complicated relative to current technology nozzle/reverser systems that are currently in commercial service.

This complexity is attributed to the multi-purpose role of these N/R/S systems: i.e., they attempt to achieve, with one system, good subsonic and supersonic performance, high noise suppression and effective thrust reversing. More detailed aerodynamic and mechanical design studies, including integration and maintainability considerations, will be required to select a N/R/S design that can meet all of the operational requirements for acceptable commercial service.

3.4.2 Preliminary Design Studies

3.4.2.1 Engine Selection

At the conclusion of the parametric systems studies, the Variable Stream Control Engine (VSCE-502) was identified as the most promising engine configuration evaluated at that time and was selected for preliminary design initiation in Task X. The single forward-valve and dual-valve VCE's were not competitive with the VSCE and consequently were not recommended for preliminary design studies.

Concurrent with the VSCE preliminary design studies, systems studies were continued on refined VCE's. This included the refined front-valve VCE-108, and rear-valve VCE configurations. The results of these refined systems studies, reviewed in Section 3.2.1, indicated the rear-valve concept as the best valved VCE evaluated in the Phase II study. Continued VCE systems studies are planned for Phase III to evaluate additional configurations which may be selected for preliminary design studies, in addition to continuing the VSCE preliminary design studies started in Phase II.

The preliminary design effort in Task X concentrated on one configuration, the VSCE-502, and was limited to the unique features of this engine. The following critical areas were studied:

- Structural evaluation of the high spool turbine disk

- Revision of engine component designs to incorporate refined technology definition including an acoustically designed fan, a low-emissions, high-efficiency duct-burner concept, a low-emissions primary burner, and an integrated rear mount structure;

- Engine bearing arrangement;
- Engine maintainability concept;
- Engine/airframe installation including pod structural support concepts, engine/airframe accessories, and improved reverser targeting capability.

The engine definition which resulted from the Task X preliminary design studies is designated the VSCE-502C. This distinguishes it from the initial parametric data-pack version of this engine, the VSCE-502, and the refined parametric study engine, the VSCE-502B. This latter engine incorporated further cycle refinements (increased OPR and CET) as a result of the refined systems studies which, because of schedule limitations, were not included in the VSCE-502C.

3.4.2.2 Structural Evaluation of the High-Pressure Turbine Disk

The high stress and temperature conditions that exist during the long periods of time the AST engines operate at supersonic cruise result in unique creep-strength requirements for the turbine and compressor disk materials. An evaluation of both conventional and advanced materials was conducted to determine their suitability for the VSCE-502C high-pressure turbine disk, and their capability to provide acceptable commercial engine life. Advanced materials evaluated for the high-pressure turbine disk would also be applicable to the low-pressure turbine and high-pressure compressor disks which are exposed to similar extremes of temperature, stress and time.

The VSCE-502C high spool has a moderate rotor-speed design, with 1300 ft/sec (400m/sec) maximum rim speed of the high-pressure turbine occurring at supersonic cruise. The high-pressure turbine disk is cooled with engine air bled from the high-pressure compressor exit. The cooling air temperature at this bleed point is at a maximum of approximately 1150°F (620°C) at the Mach number 2.4 supersonic cruise condition. The high-pressure turbine disk temperature, including the effects of the disk cooling scheme, gas path leakage, engine tolerances, engine deterioration, etc., was estimated to be equal to the cooling air temperature plus 50°F (28°C). Consequently the VSCE-502C disk was designed for 10,000 hours life at 1200°F (650°C) at the maximum rotor speed condition (Mach number 2.4 operation). Higher cruise Mach number operation or increased OPR evaluated in the refined systems studies for the VSCE-502B indicated potential performance improvements, but would result in disk temperatures in the 1300°F (700°C) range.

Figure 3.4-17 shows the allowable disk stress for WASPALOY and IN-100 materials, some advanced materials, and some very advanced materials which may be required for AST engines. As shown, all of the materials became creep limited at the higher temperatures. Waspaloy and IN-100 are used in present subsonic and military engines respectively, but are not suitable for AST engines above 1150°F (620°C) due to poor creep strength. The advanced nickel base materials, such as NASA IIb-11, were projected for the AST time period from present material research and development programs. This figure shows that the advanced materials offer a 50-70°F (28-39°C) improvement relative to Waspaloy and IN-100, and that AST may require a further 50-100°F (28-56°C) improvement in creep strength.

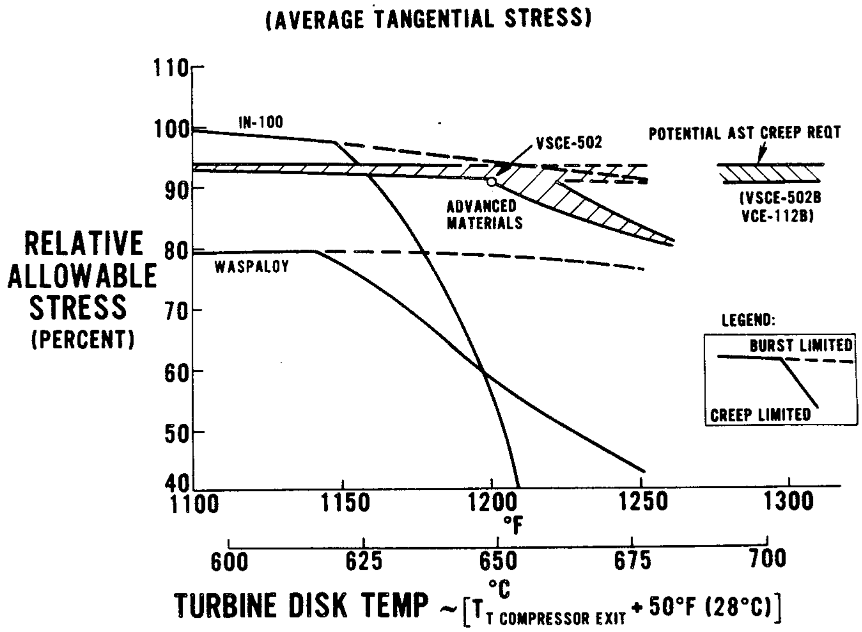


Figure 3.4-17 Allowable High Pressure Turbine Disk Stress

The impact of these material properties on the disk design is shown in Figure 3.4-18 in terms of the disk bore width required, which, in turn, sets the rotor weight required. Beyond certain width sizes, it would not be feasible to fabricate disks and expect to retain the desired material properties, or to incorporate the large disks in a practical engine design. Consequently, as shown in Figure 3.4-17, AST engines may require approximately a 150°F (83°C) improvement in creep strength relative to Waspaloy and IN-100. Otherwise, supersonic cruise Mach numbers and/or OPR limitations would have to be observed.

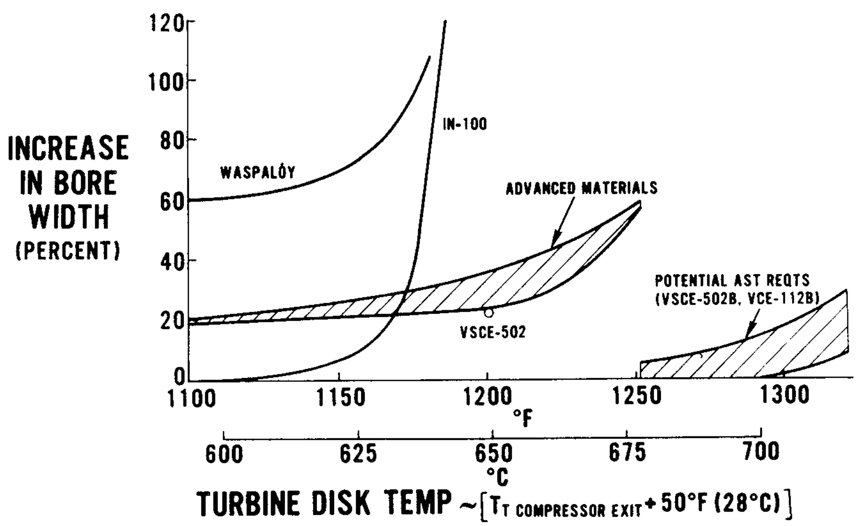


Figure 3.4-18 Impact of Advanced Materials on VSCE-502C High Pressure Turbine Disks

It should be noted that LCF (Low Cycle Fatigue) life is not expected, at this time, to be a disk design limitation for AST. The inverse throttle schedule required for low jet noise at take-off results in reduced thermal gradients, plus the long AST mission range will result in fewer take-off and landing cycles within the 10,000 hours of disk design life.

3.4.2.3 Refined Engine Cross-section

During the preliminary design studies, the major engine component designs were redefined to incorporate a refined technology definition. These refinements were based on results from related technology programs such as the AST Addendum to the NASA/P&WA Experimental Clean Combustor Program (Section 3.2.4) and the NASA/P&WA noise characteristics tests of coannular nozzles (Section 4.1); further preliminary design analysis such as the high-pressure turbine disk evaluation described in the preceding section; and the Task VIII unique components studies (Section 3.4.1). The results of this engine redesign are reflected in the refined VSCE-502C engine cross-section, shown in Figure 3.4-19.

VSCE-502C

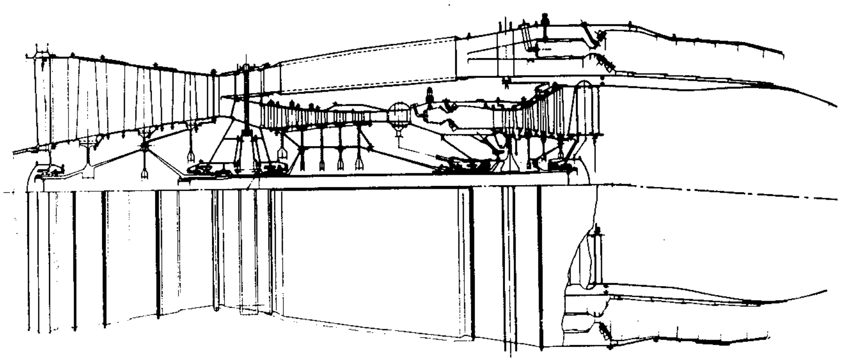


Figure 3.4-19 Preliminary VSCE-502C Cross-Section, Excluding Nozzle Design

The multi-stage fan was designed for progressively increasing rotor-stator spacing between the front and rear stages. The axial tip chord spacing is 50%, 70% and 100% (of the upstream chord) for the first, second and third stages, respectively, to reduce aft fan rotor noise propagation. A near-sonic inlet is utilized to control forward fan noise. This increased spacing allows further attenuation of the wake from one row of airfoils before it strikes the downstream row. In addition, acoustic treatment is incorporated in the fan duct between the fan and the duct-burner. This spacing resulted in a treated duct length-to-height ratio of approximately 7. The fan also incorporated the advanced technology projections described in Section 3.1.2, including variable camber inlet and exit-guide-vanes for improved efficiency and stability characteristics, and Boron/Aluminum composite material for the fan blades.

The compressor is a relatively conventional component and was not emphasized in this design phase; however, advanced technology projections were applied. Advanced materials, such as advanced high strength titanium and nickel base NASA IIb-11, are reflected in the disk sizes. The number of stages reflects advanced loading technology, and variable geometry is employed in the inlet-guide-vanes and the first two rows of stators. The compressor efficiency reflects the improvements projected for active clearance control systems (Section 4.5.2).

The primary burner design definition was based on results from the AST Addendum to the NASA/P&WA Experimental Clean Combustor Program. It is a piloted/Vorbix (Vortex burning and mixing) design which results in a 6 inch (0.15m) length increase from the parametric engine pre-mix definition that was assumed for the data-pack VSCE-502 engine. Secondary airflow passes through local swirlers for improved mixing and reduced emissions. Cooling air distribution in this burner design is consistent with the application of oxide dispersion strengthened burner liner material (Section 4.5.3).

The high-pressure turbine design incorporated the disk structural evaluation discussed in the preceding section. A ceramic material was defined for the inlet-guide-vane for light weight and reduced cooling air while the blade is a directionally solidified eutectic material for increased metal temperature capability (i.e., reduced cooling air requirement) and a high pull stress design. The disk sizes of the low-pressure turbine, another more conventional component, reflects the application of advanced materials such as NASA IIb-11, studied in the high-pressure turbine structural evaluation. Turbine efficiencies are based on these advanced materials as well as improved cooling systems and active tip clearance control systems (Section 4.5.2).

A high-efficiency low-emissions duct-burner concept was defined based on results from the AST Addendum to the NASA/P&WA Experimental Clean Combustor Program. Since the engine is sized to achieved low jet noise levels at take-off, the supersonic cruise condition requires only a low amount of augmentation, such that the duct-burner fuel-air ratio is approximately 0.015. A low-velocity, high-efficiency, pilot section was designed for this low fuel-air supersonic cruise condition. At higher fuel-air ratio conditions, such as transonic and supersonic climb, a Vorbix secondary combustion system was defined. The combination low-velocity pilot/Vorbix burner concept resulted in an increase in flow area into the pilot section and consequently an increase in the diffusion requirement between the fan exit and the duct-burner inlet. This led to the design of an advanced diffuser concept to avoid unacceptable boundary layer buildup and corresponding engine length penalties. A branch diffuser concept was defined as shown in the engine cross-section, which consisted of two sealed circumferential vanes upstream of the pilot section. This divides the duct airflow into three streams, thereby reducing the equivalent diffuser conical angle.

The high spool is supported by two bearings: one thrust bearing located at the intermediate case and one roller bearing located under the primary burner. The low spool is supported by three bearings: one roller bearing located under the fan inlet case, the thrust bearing located at the intermediate case, and one roller bearing supporting the low-pressure turbine.

A two-plane engine mount system was defined for the VSCE-502C. The front mount is located over the fan inlet case to obtain as much axial separation as possible between the two mounts. The rear engine mount is located just upstream of the duct-burner pilot section. The engine loads are passed across the bypass stream with a series of aerodynamic struts and tied to the turbine case, as shown in Figure 3.4-19. Only vertical and side loads are transmitted to the rear mount; a square spline is provided to allow axial differential growth between the gas generator and the rear mount. A thermal spring is included in order to isolate the rear mount from the thermal growth of the turbine case. Axial (thrust) loads are taken out at the front engine mount only. Further design study is required to integrate the rear mount and duct-burner with minimum impact on engine length, duct-burner operation, engine accessibility, and engine/airframe installation.

3.4.2.4 Alternate Engine Bearing Arrangement

An alternate engine bearing arrangement was defined as shown in Figure 3.4-20. The high-spool roller bearing located under the primary burner was replaced with a "piggyback" bearing, located aft of the high turbine, between the high and low spools. This arrangement eliminates the requirement for a strut across the primary burner diffuser and consequently offers a potential reduction in complexity of primary burner design. This is an important consideration when taking into account the burner complexity required for a low-emissions design. In addition, this bearing compartment is removed from a relatively hot region of the engine which will result in improved bearing life and reduced oil-cooling requirements.

Further detailed design analysis is required before a final engine bearing arrangement is selected. This would include detailed rotor/frame critical speed analysis and the effect of advanced damped bearing technology on the tip clearances of the alternate bearing arrangement.

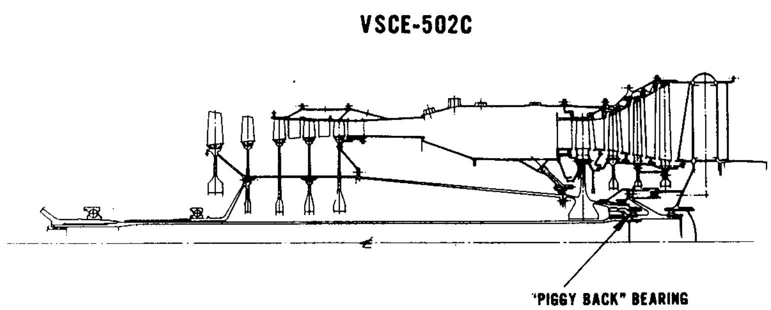


Figure 3.4-20 Alternate High Spool Bearing Arrangement for VSCE-502C

3.4.2.5 Engine Maintainability Concept

The VSCE-502C preliminary design utilizes a modular concept to provide the maintenance capability to meet commercial engine requirements. The major engine components constitute separate engine modules for ease of removal, replacement and overhaul; thus minimizing aircraft down time and increasing system productivity.

Figure 3.4-21 shows the preliminary engine modular maintainability/accessibility concept for the VSCE-502C. The engine modules shown in this "exploded" drawing are:

- Fan
- Intermediate case
- Compressor
- Fan-duct case
- Primary burner
- High-pressure turbine
- Low-pressure turbine inlet-guide-vane
- Low-pressure turbine and shaft
- Engine tailcone
- Rear mount
- Primary nozzle
- Duct burner and nozzle

All of the modules are separated axially, as shown by the dotted lines, except for the fan duct case. This case is split into a top and bottom half which could be hinged for access to the gas generator with the engine mounted on the wing. In addition, a bifurcation was incorporated in the fan-duct case to provide engine services to the gas generator and to allow boroscope inspections without opening or removing the fan-duct case.

Further preliminary design studies are needed to evaluate the impact of shortening the fan-duct diffuser on the front/rear mount separation, overall engine length and weight, and access to the gas generator.

3.4.2.6 Engine/Airframe Installation

Basic pod geometry was set by the engine, the inlet and the nozzle/reverser systems. Because of the impact of pod geometry on installed performance, sensitivity of the pod to engine and airplane design considerations is a prime factor in these AST studies. This includes aerodynamic, thermal, structural, maintenance, and accessory considerations. Pod geometry, from an integrated engine/airplane viewpoint, was therefore included in these initial preliminary design studies.

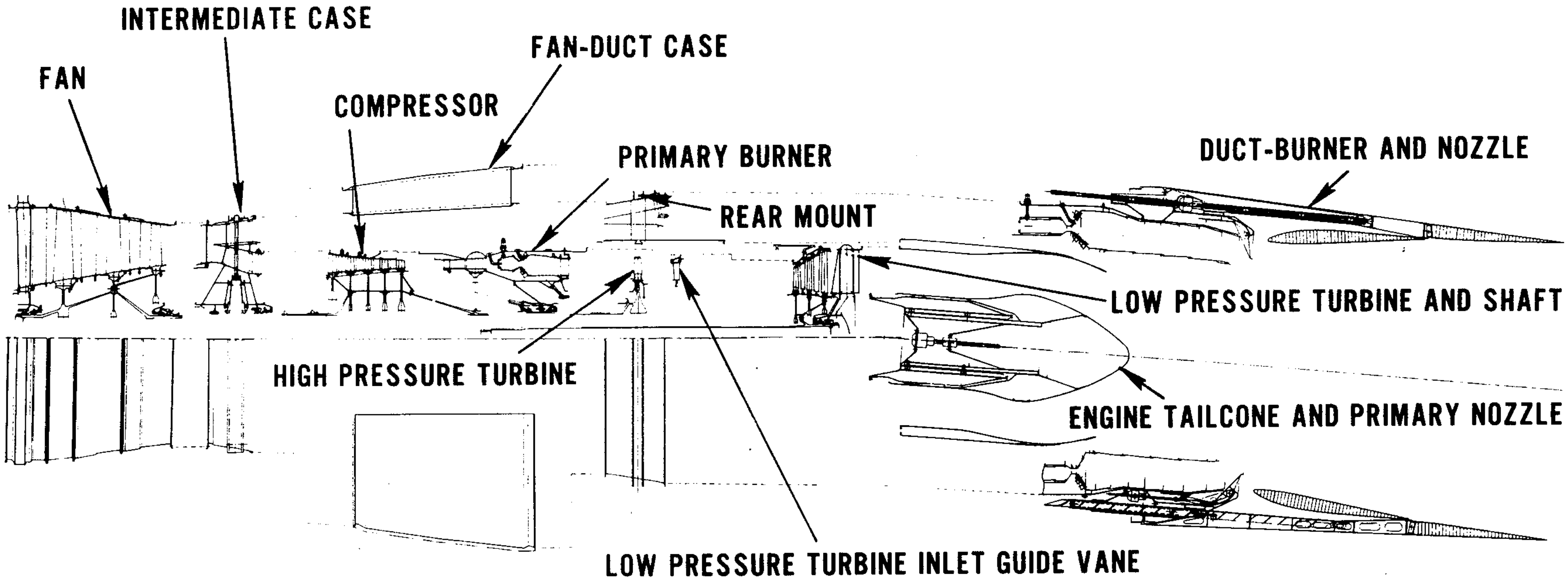


Figure 3.4-21 VSCE-502C Modular Concept

The overall pod arrangement for a representative VSCE configuration was defined at the outset of this design study by Boeing (Figure 2-5). This drawing highlights the unique pod characteristics. As shown, the inlet and nozzle systems are major components that almost dominate the AST engine relative to subsonic engines. Figure 2-5 and the attending pod geometry requirements (Section 2.3.1) were observed in the Task X preliminary design of the VSCE-502C.

A pod drawing for the VSCE-502C is shown in Figure 3.4-22 and reflects these pod geometry considerations. Due to space limitations and support structure above the engine, the engine accessories were mounted on the bottom of the engine. The airframe PTO (Power Take Off) projects into a wing cavity with access through an opening in the upper surface of the wing.

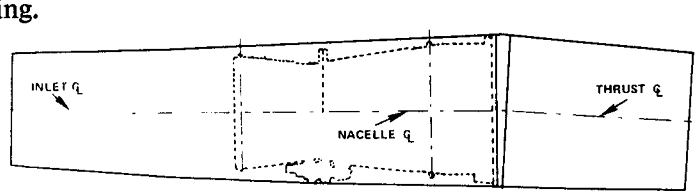


Figure 3.4-22 VSCE-502C Pod Drawing

Figures 3.4-23 and -24 are schematic drawings of two possible support arrangements for AST engines. These isometric drawings show the load vectors acting on the engine at the front and rear mount planes. Figure 3.4-23 represents a more conventional support concept where the wing structure is tied directly to the engine structure. For this arrangement, the inlet and nozzle/reverser systems are supported by the engine structure. Figure 3.4-24 represents an advanced structural nacelle concept. This structural nacelle supports the engine, the inlet, and the nozzle/reverser systems. Integration design studies are required to quantitatively compare these two concepts in the areas of structural redundancy, engine case distortions, weight characteristics, and maintainability features.

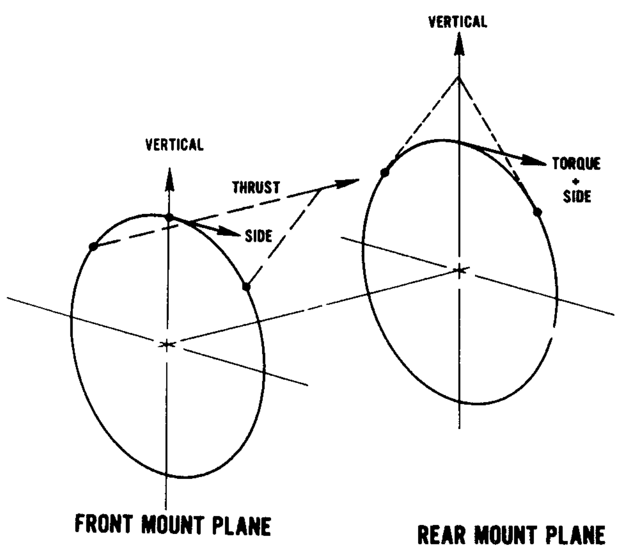


Figure 3.4-23 Conventional Engine Support Concept

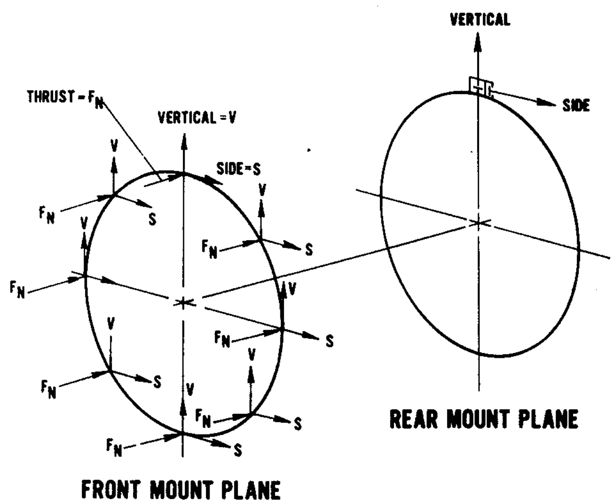


Figure 3.4-24 Structural Nacelle Engine Support Concept

3.4.2.7 Summary

The Task X studies initiated the preliminary design of the VSCE concept, concentrating on the unique features of this AST engine. These studies included a structural evaluation of the high-pressure turbine disk, an engine cross-section incorporating refined technology definition, engine bearing arrangement, engine maintainability and engine/airframe installation.

Further preliminary design studies are required in many areas of the VSCE-502C engine. These include:

- Continued evaluation of variable geometry engine components, such as the fan, turbine and primary nozzle, to assess the system benefits versus the resulting additional mechanical complexity.

- Detailed integration studies of the duct-burner with the fan-duct diffuser, the rear mount and the nozzle system. This would include the impact on overall engine length and weight, front/rear mount separation, access to the gas generator and duct-burner configurations with improved emissions and performance characteristics resulting from the on-going ECCP.

- Detailed structural analysis of engine rotor and bearing arrangements, incorporating advanced high temperature technology for these components.

- Incorporation of inspection, maintainability and accessibility features that are critical for successful commercial service.

- Continued integration of the overall engine/inlet/nozzle/airframe propulsion system including aerodynamic, thermal, structural, maintenance and accessory considerations.
- Cost/weight/performance trade studies, particularly for many of the advanced materials and component technologies, to optimize the overall system economics.
- Refinement of the nozzle system to incorporate results from the continuing coannular nozzle tests as they become available.

4.0 TECHNOLOGY PROGRAMS

One of the primary objectives of the SCAR/AST Propulsion System Studies is to identify the engine-related technologies that offer the greatest potential for improving the environmental and economic characteristics of advanced supersonic commercial transports. The Phase I studies consisted of broad parametric evaluations of a large number of conventional and unconventional engine concepts. These studies showed that advanced propulsion technology has the potential for significant improvements in the environmental and economic areas. Critical technology programs were recommended in the Phase I Final Report (NASA CR-134633, January 1974). The Phase II studies consisted of more concentrated parametric studies including parametric airplane/engine integration evaluations and initiation of preliminary design studies. This phase identified the Variable Stream Control Engine (VSCE) as one of the most promising engines identified in the AST propulsion system studies. A rear-valve Variable Cycle Engine was defined late in the Phase II effort as also being an attractive engine concept. Based on the Phase II study engines, critical technology programs recommended in Phase I have been updated and expanded to be consistent with the Phase II results. This section discusses the technology programs that are critical for each of these Variable Cycle Engines. In addition, the technologies that are critical to the rear-valve engine above, and additional technology requirements that are applicable in general to advanced supersonic engine concepts are also identified.

The critical technology requirements for both Variable Cycle Engine concepts are listed in Table 4-I. The items preceded by stars represent unique technologies that should receive emphasis as highest priority technology programs. Unlike the other technologies listed in Table 4-I which are generally applicable to all advanced subsonic and supersonic commercial and military engines, the starred items are special requirements for the two most promising AST Variable Cycle Engines. Research and technology programs and a preliminary plan for an environmental demonstration program have been formulated for the starred areas. The remaining technologies in Table 4-I are equally critical to the eventual environmental and economic success of the candidate AST propulsion systems. Some of these areas will be advanced by currently active programs not directly related with the SCAR/AST program, such as the NASA-sponsored ECCP for main burner emissions. In addition, continuation of the SCAR propulsion and integration studies will define more specific technology requirements for the low noise inlet as well as aerodynamic and structural technology for the pod.

In addition to the critical technologies in Table 4-I, Table 4-II is a list of critical requirements for the rear-valve VCE concept. These technologies compliment those in Table 4-I.

Although not as critical as the requirements in Tables 4-I and 4-II, there are additional engine-related technology areas that will also require research and technology programs. Some of these are listed in Table 4-III. These individual technologies do not pose the impact to the overall propulsion system as do the technologies in Tables 4-I and 4-II. Nevertheless, advancements in each area are listed in Table 4-III will be required for a successful AST propulsion system. Definition of specific technology advancements in these areas will be provided by continued refinement and design studies of the most promising engine concepts. The following sections describe the critical technologies listed in Table 4-I. Program recommendations are also described.

TABLE 4-I

CRITICAL TECHNOLOGY REQUIREMENTS FOR BOTH VARIABLE CYCLE ENGINE CONCEPTS

- ★ Low noise coannular nozzle
- ★ Low emissions duct burner
- ★ Variable geometry multi-stage fan
- • Low emissions primary burner
- • Hot section technology
  - • Directionally solidified eutectic blades
  - • Ceramic vanes, endwalls and tip seals
  - • High creep strength disk material
  - • Active tip clearance control system
  - • Oxide dispersion strengthened burner liner material
- • Full-authority electronic control system
- • Variable geometry low noise inlet
- • Propulsion system integration

★ Emphasis on unique technologies

TABLE 4-II

CRITICAL TECHNOLOGY REQUIREMENTS FOR REAR-VALVE VARIABLE CYCLE ENGINE CONCEPT

- Rear flow inverter valve
- Rear turbine
- Nozzle/ejector system
- Stability during valve transition
- Fail-safe valve design
- Low spool critical speed control

TABLE 4-III

ADDITIONAL TECHNOLOGY REQUIREMENTS FOR BOTH VARIABLE CYCLE ENGINE CONCEPTS

- Advanced turbine designs
- Advanced variable geometry compressor
- High temperature lubricants
- Advanced accessories and drive systems
- High temperature bearings and seals
- Light-weight rotor structure
- Propulsion system safety features
- High temperature, light-weight acoustic treatment
- Low noise thrust reverser

4.1 LOW NOISE COANNULAR NOZZLE

The most promising method for reducing jet noise with minimum penalty to the propulsion system is based on Variable Cycle Engines with coannular nozzles. P&WA is conducting a test program under NASA sponsorship (NAS3-17866) to evaluate this concept and to compare noise characteristics of various suppressor configurations. Based on static test data, unsuppressed coannular nozzles may have the potential for significant reductions in jet noise without the performance penalties and other burdens such as weight, cost and complexity associated with mechanical suppressors. This potential noise reduction is shown in Figure 4-1 for various levels of specific thrust for a representative AST engine. Based on coannular nozzles having unique velocity profiles similar to that shown in Figure 4-1, a significant reduction in jet noise has been measured. This profile is obtained through design features of Variable Cycle Engines combined with unique throttle scheduling techniques for the combustors of the engine and bypass flow streams. Figure 4-3 illustrates the basic principle that provides this natural suppression for coannular nozzles. The left side of Figure 4-3 shows the velocity profile for a single stream nozzle. The right side shows a coannular nozzle. At the Station X downstream from the nozzle exit plane, the profile on the left for the single stream nozzle shows the effect of mixing and momentum exchange with ambient air. The shaded velocity profile indicates the maximum core velocity has not been reduced. For the coannular nozzle, the maximum velocity in the bypass stream is reduced by mixing and momentum exchange with air on both the outer and inner surfaces. The peak velocity has been reduced at the measuring Station X and jet noise is correspondingly lower. The net effect for the coannular nozzle is equivalent to an increase in BPR with a lower jet velocity and reduced noise for the overall engine. The next major step in evaluating the potential benefit of coannular nozzles is to determine the jet noise and performance characteristics at conditions that simulate flight velocities. A follow-on program is in progress to begin evaluation of the flight characteristics. In addition, three other programs related with the noise and performance characteristics of supersonic nozzles have been recommended. These programs are described in the following sections.

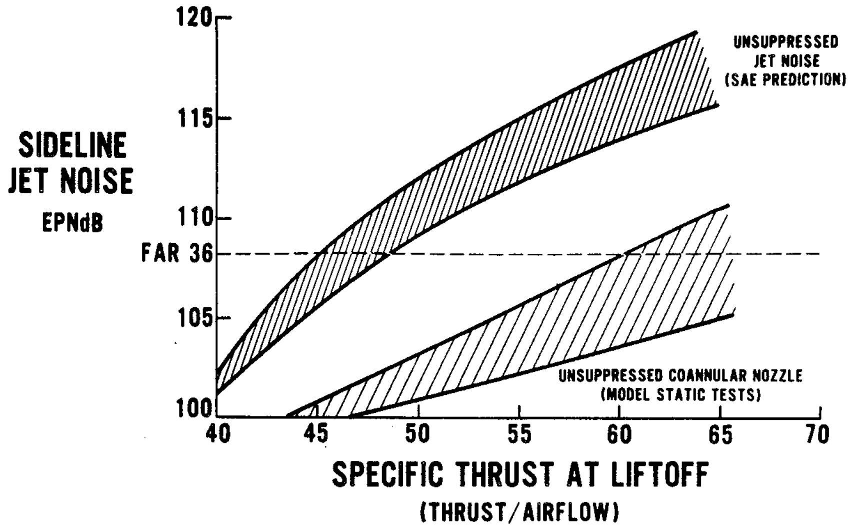


Figure 4-1 *Potential Improvement in Jet Noise from Coannular Nozzles*

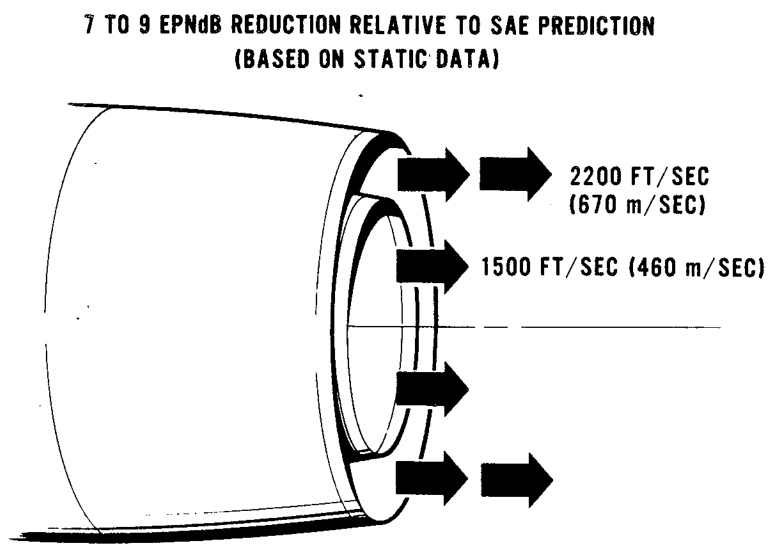


Figure 4-2 *Coannular Nozzle Velocity Profile*

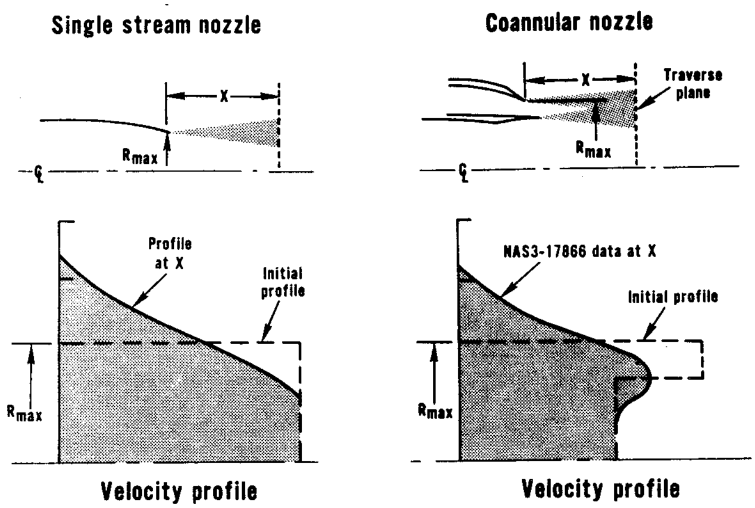


Figure 4-3 *Nozzle Velocity Profiles*

4.1.1 Coannular Nozzle Flight Effect Program

The objective of this program is to evaluate the effects of external flow on the noise benefits demonstrated statically for coannular exhaust systems. The thrust characteristics of these nozzles will also be evaluated. Model nozzle designs selected from the current static program will be evaluated. These models will be tested over a range of external flow conditions that simulate flight speeds between static and climb-out levels. Noise measurements will be made in a facility that provides the unique capability of testing coannular nozzle models with two-stream velocity and temperature control in a large, open jet velocity field in an anechoic environment. Thrust characteristics will be evaluated in a large subsonic wind tunnel, which has the required thrust balance and separate stream velocity control capability necessary to evaluate coannular nozzle systems. Based on the results of these tests, preliminary methods will be established to extrapolate static data to predict inflight noise. Work has begun on this recommended program and preliminary results should be available in the first quarter of 1976.

Since the coannular nozzle system provides an inherent degree of jet noise reduction without requiring mechanical suppressors in the hot exhaust stream, higher levels of duct-burner augmentation are possible than were possible when the nozzle test program was planned. The range of test conditions should be extended from 1500°F (1090°K) to 2500°F (1640°K), with velocities up to 3200 ft/sec (970 m/sec) in the bypass stream.

4.1.2 Ejector Program

The results of the static test program indicated that the jet noise suppression/performance characteristics were affected by acoustic treatment on the inside of the ejector. Since all of the configurations, both suppressed and unsuppressed, were tested with the same ejector, the design was not optimized for noise suppression or performance. In order to determine the potential effects of flight-type acoustically treated ejectors, an investigation is recommended into noise and performance trades due to ejector configuration and treatment design. This investigation will include the coannular reference configuration and representative suppressed configuration. Basic ejector variables will be evaluated including the inner contour and the inlet design and location. Acoustic treatment design parameters, such as facing sheet porosity and bulk or honeycomb backing material, will be investigated along with the preceding ejector variations on both basic configurations. This study will be done over a range of internal flow properties at both static and take-off conditions. Results of this study will identify the noise-performance trades associated with the use of treated ejectors on candidate AST engine cycles.

4.1.3 Nozzle Area Ratio Program

The initial test data for the coannular nozzle exhibited significantly lower noise levels relative to conventional jet noise predictions. Since this benefit is related with the rapid mixing of the high velocity outer stream, the outer to inner throat area ratio is an important factor in the noise benefits obtained. In order to determine the range of area ratios over which the coannular noise benefit exists, a program is recommended to determine noise levels as a function of this area ratio. The existing P&WA test rig and instrumentation section can accommodate an area ratio range from approximately 0.3 to 2.0. A test program can be structured that will provide data over a configuration range that is significantly larger than the range of 0.75 to 1.2 being evaluated in the present program. A matrix of operating conditions will be evaluated for each area ratio to provide data that can be used for optimization of the coannular benefits for the promising AST engine cycles.

4.1.4 Jet Noise Prediction System for Coannular Nozzles

Static data from the current test program has demonstrated that the existing SAE jet noise prediction procedures are inadequate for estimating jet noise for Variable Cycle Engines with coannular nozzles. The objective of this recommended program is to develop an empirical procedure that will allow accurate predictions based on an orderly and consistent interpolation of the test data. In order to screen potential cycles from an acoustic viewpoint, particularly if community noise footprints are to be used as selection criteria, it is necessary to organize the data into a computerized prediction system. The output of this prediction system will be tabulation of standard day jet noise spectra at angles from 65° to 165° for a constant radius and for a specified range of fan and primary operating conditions. This will allow an estimate of perceived jet noise for a full size engine at any altitude by using standard extrapolation and scaling procedures. This procedure can also be used to predict aircraft flyover noise, including community noise footprints, when suitable corrections for aircraft forward speed are determined as discussed in the program described in Section 4.1.1. The prediction system can be computerized in a manner to easily assimilate future growth of the data base, especially the results required from the wind tunnel test program.

As is obvious from these recommended programs, the potential noise and performance benefits for coannular nozzles are being emphasized. There are, however, other technology requirements for these supersonic coannular nozzle systems including the following: alternate high performance configurations for supersonic operation; lightweight variable nozzle geometry designs to meet the contrasting requirements of low jet noise and high performance at supersonic conditions; an acoustically treated ejector to compliment the coannular jet noise benefit; a targetable thrust reverser; and advanced materials and cooling systems to minimize the weight of these components. The impact of these additional requirements on the overall nozzle configuration must be determined to compliment the coannular noise benefit and to refine the coannular nozzle design.

Following these programs, a full-scale demonstration of the coannular nozzle can be conducted as described in Section 4.9.

4.2 LOW EMISSIONS DUCT-BURNER

The duct-burner is a critical technology requirement for the two most promising Variable Cycle Engines. Duct-burners are used to augment engine thrust during take-off and climb. For supersonic cruise, these augmentors are throttled back to low fuel/air ratios. Advanced combustion technology is required to provide low emissions and high efficiency without compromising the dimensions, complexity, and operating characteristics (stability, lean blow-out and combustion noise) of these duct-burners. Because of the low noise feature of these engines, the duct-burner operating conditions are much different from conventional after-burners used for military engines. Primary burner concepts and configurations being evaluated in the NASA-sponsored ECCP are not directly applicable to these duct-burners because of the differences in air conditions (pressures, temperatures and flow rates) entering these burners. These differences in operating conditions, combined with the low emissions and noise, and high efficiency requirements, set the scene for applied combustion research for these AST duct-burners. The following three-phase program is recommended.

Phase 1 – Duct-Burner Analytical Screening Program

The objective of this program is to analytically screen several combustion design concepts that are applicable to duct-burners for AST Variable Cycle Engines. The most promising concept would then be selected for experimental evaluation in the recommended Phase 2 program.

This analytical screening will expedite the overall AST duct-burner program by eliminating the less attractive concepts prior to the experimental phase. The extent and expense of the experimental program are thereby reduced. The analytical screening will consist of:

- defining burner dimensions
- estimating performance characteristics
- emissions estimates for the airport vicinity and also at supersonic cruise
- preliminary design study
- cost and weight estimates

- servicing, reliability and maintainability comparisons
- determining the impact of advanced, high temperature materials and cooling concepts on performance and emissions characteristics
- compatibility of advanced fan and diffusers with the candidate burner concepts

Based on an overall comparison, the most promising duct-burner concept will be selected for experimental evaluation described in the following section.

Phase 2 – Experimental Evaluation of the Selected Duct-Burner Concept

The objective of this program is to experimentally evaluate the emissions and performance characteristics of the most promising duct-burner concept selected from the Phase 1 analytical screening.

Approximately six variations of the selected burner configuration will be evaluated in an experimental rig facility which can simulate the entire range of engine operating conditions, including sea level take-off, transonic climb and supersonic cruise conditions. Special instrumentation will be used to measure combustion efficiency, pressure losses, emissions and noise. This experimental program will provide the data base and substantiation for the next phase which is demonstration of this duct-burner concept using an existing engine.

Phase 3 – Engine Demonstration of the Selected Duct-Burner Concept

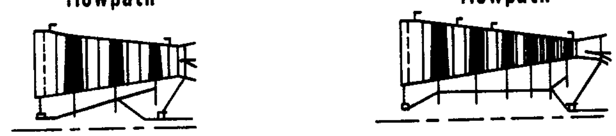
There are three possible approaches for this demonstrator program. These are described in Section 4.9. Each approach includes demonstration of the selected low emissions duct-burner concept along with other critical technologies that are required for the most promising Variable Cycle Engines.

4.3 VARIABLE GEOMETRY MULTI-STAGE FAN

The third critical technology requirement for Variable Cycle Engines is a multi-stage fan with variable geometry. Figure 4-4 summarizes the fan flowpath and design characteristics for the Variable Stream Control Engine (VSCE-502B) and for the rear-valve Variable Cycle Engine (VCE-112B). The variable geometry feature for these fans consists of variable stators as indicated in Figure 4-4 plus a possible variable geometry splitter behind these fans. This level of variable fan geometry, in conjunction with variable geometry for the supersonic inlets and nozzles, provides the following potential benefits for these Variable Cycle Engines:

- Improved surge margin. This provides the capability for better off-design matching characteristics for these engines during subsonic and supersonic cruise.

Representative fan configurations for VCE's



	VSCE-502B flowpath	Rear valve VCE-112B flowpath
FPR	3 to 4	4.5 to 6
BPR	1 to 1.5	2.5
$U_T/\sqrt{\theta_{T2}}$ ft/sec	1600 to 1800	1600 to 1800
(m/sec)	(490 to 550)	(490 to 550)
No. of stages	2 to 3	4 to 6
Variable Geometry	IGV + EGV (1)	IGV + 2 stators + EGV

(1.) IGV = Inlet Guide Vane
EGV = Exit Guide Vane

Figure 4-4 Multi-Stage Variable Geometry Fan Requirements

- High-flowing the engine at part-power operating conditions. This feature is beneficial for reducing jet noise during take-off (to supplement the coannular noise benefit). It also improves installed performance at subsonic cruise by making the engine swallow the inlet airflow rather than spilling or bypassing it. This capability to high-flow the engine in order to match the inlet airflow schedule further improves installed performance at subsonic cruise by filling the nozzle exit area and reducing the boat-tail drag. Further evaluation of this flow matching capability may substantiate the potential for significant improvements to the supersonic inlet. These improvements would be in terms of a less complex inlet design, brought about by reducing the requirement for bypass doors during subsonic cruise and blow-in doors for maximum power during transonic climb.

- Reduced windmilling drag in the event of an inflight shutdown. This feature has special significance for supersonic transports because of the high drag associated with an inoperative engine at supersonic conditions and the corresponding effect on the airplane design.

In addition to these potential variable geometry benefits, there are several other advanced technology areas and related design features which may be applicable to the multi-stage fans of these Variable Cycle Engines. Some of these are:

- Advanced aerodynamic airfoils such as controlled shock designs which may improve the fan efficiency, especially for the high tip speeds projected for these advanced engines.

- Elimination of part-span shrouds by using low aspect ratio, composite fan blades or by improving the tip seal designs to incorporate the shroud in the end-wall region.

- Reducing the front case diameter of the engine by designing the fan for slightly lower hub/tip ratios. This is an installation improvement for the nacelle design and was identified in the Phase II integration studies.

- Reducing the exit Mach number for the fan in preparation for the duct-burner. This requires more diffusion in the fan and, for a constant surge margin, tends to reduce the allowable pressure ratio per stage.

- Incorporation of low noise features in the fan design such as wide blade-to-stator axial spacing, selective matching of the number of airfoils in adjacent rows, and various combinations of aerodynamic loading and rotational speeds.

- Design for compatibility with a low-noise, sonic inlet which is especially appropriate for these AST engines because of the variable geometry inlet required for supersonic operation. This inlet can accommodate the area change to provide the near-sonic internal condition to prevent engine noise from being released through the inlet. The near-sonic condition can be obtained not only for take-off but also at approach which is more difficult because total engine airflow is reduced.

The summation of these technologies present a series of fan requirements that are unique for AST Variable Cycle Engines. The following fan program is recommended to analytically evaluate these features, to incorporate the most promising in a representative fan design, and then demonstrate these features in an experimental program.

4.3.1 Multi-Stage Variable Geometry Fan Program

A two phase program is recommended; a design study and an experimental demonstration.

The first phase consists of aerodynamic and acoustic design studies to evaluate advanced fan technologies for the most promising Variable Cycle Engines. Drawing from the conceptual and preliminary design studies being conducted as part of the SCAR/AST propulsion system studies, a more detailed evaluation of these potential advanced technology features will be conducted. The product of this effort will be a baseline design of a multi-stage, variable geometry fan that reflects the optimum balance between aerodynamic and acoustic features. The objective of this design is to incorporate as many compatible advancements as possible to attain the aerodynamic goals listed in Table 4-IV. These goals are in addition to the goal of reducing fan noise released from the inlet and nozzle. For reference, the fan characteristics of current engines are also listed in this table. The numbers of stages and pressure ratios shown in Table 4-IV as goals for the AST fan cover the ranges for the two most promising Variable Cycle Engines identified in the Phase II propulsion system studies.

The second phase is to utilize some of the hardware from an existing NASA fan rig, add a stage, and use it to demonstrate the basic aerodynamic and acoustic advancements that are selected from the design study and are considered critical for AST engines. This approach of modifying an existing fan rig is recommended to minimize cost of the experimental portion of this program. There are at least three existing experimental fans from other NASA programs that might be considered for this demonstration program.

TABLE 4-IV

FAN TECHNOLOGY STATUS AND GOALS

	Number of stages	Pressure ratio
Current engines	3	2.2 to 2.8
AST goals	2 to 6	3 to 6

	Full span efficiency (%)	Tip speed ft/sec (m/sec)	Average Pressure Ratio per Stage
Current engines	80 to 84	~1500 (~ 460)	1.3 to 1.4
AST goals	84 to 86	1600 to 1800 (490 to 550)	1.5 to 2.0

4.3.2 Fan/Duct-Burner Noise Program

With the possibility of using coannular nozzles to reduce jet noise, and sonic inlets to reduce fan noise propagating from the inlet, the fan noise that is released from the fan duct and nozzle remains a potentially significant noise source. Furthermore, the effect of the duct-burner on aft fan noise has not been established. A study is recommended to determine the effects of fan noise propagating through the temperature rise associated with the duct-burner, and to evaluate the possibility of reducing noise at approach by reducing fan speed and pressure ratio while using partial duct-burning to maintain thrust. Although the duct-burner would normally be off during approach, it could be used to allow the engine to achieve the required approach thrust at a lower fan speed. The fan noise dominates at approach conditions and a net improvement in total noise may be obtained even though jet noise would increase. From the results of these studies, the optimum cutback and approach operating conditions can be identified. The effect on engine emissions would also be determined for the power settings being considered.

Analytical studies have suggested that duct-burning may have a favorable effect on suppressing rearward fan noise. By adding heat downstream from the fan, the resulting increase in Mach Number may cause some of the normally propagating modes to be cut off and to decay in the duct, reducing blade passing noise. From preliminary analysis of this effect, reported in NASA-SP-207, it is concluded that a possibility exists for selectively and significantly reducing pure tones that propagate from the fan through a high temperature region in the fan duct. It is recommended that an analytical model be formulated to study the propagation of fan tones through a representative AST duct-burner flow stream. The input to this model will be the propagation acoustic "spinning modes" produced by the fan. The propagation model will account for both the effects of the duct contour on mode propagation and the effects of the temperature rise through the duct-burner at various operating conditions. Based on this model, recommendations will be made on design of the optimum duct geometry for candidate AST engines, and on the use of partial duct-burning on approach to suppress rearward fan noise. Along with analyzing the model, an experimental program will be defined to verify key characteristics and assumptions of the model.

The experimental evaluation of this program will focus on the propagation of noise through turbulence and the effect of temperature rise from the duct-burner on fan tone noise. A two dimensional model of a full scale duct segment, incorporating a burner assembly, will be fabricated for testing. It may be possible that representative hardware from other NASA programs such as the ECCP could be used. The duct segment will be installed in a facility having an upstream noise source and capable of simulating representative flow Mach numbers through the burner section. Measurements of noise transmission will be made over a range of temperature levels and flow conditions representative of the cutback and approach power settings. Results will be used to verify and refine the analytical models for use in later engine design studies.

A second benefit from this program will be the evaluation of combustion noise generated by the duct-burner. Evidence suggests that noise from the duct-burner may contribute to the far field noise spectrum of AST engines. Two potential noise-generating mechanisms have been defined: indirect combustion noise generated by convection of temperature oscillations as they pass through the duct-burner and nozzle; and direct combustion noise attributed to the unsteady release of heat during the combustion process. Experimental investigations of combustion noise could be included as part of this fan/duct-burner noise program. The same facilities and hardware can be used. Noise would be measured over a range of duct-burner operating conditions. Test data could then be used to evaluate analytical models which would be used to predict full-scale duct-burner noise for the candidate AST engines.

4.4 LOW EMISSIONS PRIMARY BURNER

The P&WA Experimental Clean Combustor Program (ECCP) sponsored by NASA is concentrating on advanced combustion concepts and designs for primary burners of subsonic engines in order to reduce emissions in the airport environment and also at high altitudes. An AST addendum to this program was conducted to reduce NOx at high altitude supersonic cruise conditions without compromising other burner requirements such as efficiency, stability, weight, cost and emission characteristics at other operating conditions. Application of these results to AST study engines (Section 3.2.4) resulted in two basic conclusions. First, the advanced burner technologies that will eventually be applied to future subsonic engines will require further improvements to meet proposed emission levels for AST engines (Table 3.2-XVII). The reason for needing further improvements is due to the differences between AST engine cycles and advanced subsonic engine cycles. For example, the AST engines have lower bypass ratios, lower overall pressure ratios, and employ augmentors. These factors have adverse effects on subsonic TSFC. During the take-off and landing cycle, the higher fuel flow of the AST engines requires lower emissions per pound of fuel burned to meet the EPA parameter proposed for AST engines. The right-hand column of Table 3.2-XVII shows the percent improvement required for each type of pollutant. The second conclusion is the ECCP data from the AST addendum show the potential to reduce NOx by a factor of two at supersonic cruise relative to current technology burner designs in the same engine cycle. This is significant in that NOx is the high altitude pollutant that has received the most concern. Whether this reduction in NOx is acceptable for AST engines or whether further improvements are required can only be determined by intensive measurements of the cyclic nature of the stratosphere's chemistry.

To further explore the emission characteristics of advanced burner concepts for AST Variable Cycle Engines, a continuation of the work started during the ECCP AST Addendum is recommended. This would be an analytical and experimental program to control fuel/air mixtures and residence times in the hot combustion zones. In addition to varying the fuel schedule by the use of zoning and staging techniques, variable geometry for controlling changes in air schedules will be evaluated. It may be possible to use ECCP Phase II hardware for this recommended program.

4.5 HOT SECTION CRITICAL TECHNOLOGY REQUIREMENTS

Based on the initial Phase I study results, two critical hot section technologies were identified and programs were recommended in the Phase I Final Report. These were high strength turbine blade materials (directionally solidified eutectic alloys) which limit the design speeds of the engine rotors, and high temperature vane and end-wall materials (ceramics) that will reduce cooling air bleed and improve turbine efficiency. Summaries of the program recommended for these blade and vane requirements are described in NASA CR-134633, Pages 87 and 88. To complement these earlier recommendations, three additional requirements have been identified for the hot sections of Variable Cycle Engines. These are high creep-strength turbine disk materials, active tip clearance control technology and Oxide Dispersion Strengthened burner liner material.

4.5.1 High Creep Strength Turbine Disk

Section 3.4.2.2 of this report describes the design analysis of the turbine disk and the attending creep strength requirements. A program is recommended to determine the feasibility of various approaches to meet the creep strength requirement for these turbine disks. Some of the approaches to be explored in this high temperature disk program are: new alloys to extend the high temperature creep strength capability beyond some of the research alloys that are currently being evaluated such as NASA IIB-11; composite disks including fiber-wound, multi-alloy or laminated configurations; and cast disks fabricated by hot isostatic press techniques, possibly improved by thermal-mechanical treatment such as explosive shocking. The goal for these advanced disk materials is to obtain a 97,000 psi (6.7×10^8 N/m^2), 1250°F (680°C), 0.2% creep strength in 10,000 hours with no compromise to either low cycle fatigue or oxidation resistance characteristics relative to current disk materials.

4.5.2 Active Tip Clearance Control System

Preserving engine component efficiency through the life of the candidate AST Variable Cycle Engines will depend on effective sealing of the airflow throughout the engine flow-path and especially at the blade tips. Rapid engine power transients which result in differential thermal growth between rotor assemblies and cases, engine structural deflections from case temperature gradients, and aircraft flight and ground induced loads all contribute to significant running clearances in these critical seal regions. A program is recommended to conduct exploratory research and analysis of systems to actively modulate turbine and compressor blade tip clearances throughout the flight envelope. Compressor and turbine operational characteristics that affect gas path sealing will be analyzed and various concepts will be studied to compensate for factors which contribute to operating clearance. For example, compressor blade tips may show a steady-state cruise operating clearance of 20 mils when designed for minimum clearance at sea level take-off conditions. Mechanical, pneumatic, and thermal schemes for activating tip seal controls, will be appraised with a goal of reducing clearance to near zero at the cruise point. Concepts for reducing the clearances will be evaluated and cost, weight and complexity differences will be considered relative to potential TSFC reductions for the AST engine mission.

4.5.3 Oxide Dispersion Strengthened Burner Liner Material

Oxide Dispersion Strengthened (ODS) sheet alloys have the potential to retain high creep strength at elevated metal temperatures relative to the best liner materials currently available for gas turbine burner liners. Although definition of the properties of this ODS material is in the preliminary stages, data are available which allow metal temperature projections to levels which are several hundred degrees higher than present day sheet materials. This capability will have special significance when designing the cooling air distribution for advanced, low emission burner systems, including main-burners and thrust augmentors. Furthermore, the need for higher temperature liners for the main burner system is especially critical for AST engines because the compressor exit temperature at supersonic cruise may be as high as 1300°F (700°C). Without high temperature liner materials, performance may be penalized by restrictions on the overall engine pressure ratio at supersonic cruise. This material may also be applied to the duct-burner design to reduce the liner cooling air requirement and thereby improve the thrust efficiency (thermal profile) in the bypass stream.

A program is recommended to first identify the composition and processing techniques for candidate ODS sheet materials. This initial program would be followed by the evaluation of fabrication techniques and establishing design data leading to the fabrication and testing of experimental burner liner segments. Engine tests of the most promising concepts in high temperature operating environments would verify the applicability of this type of material to the main-burner and duct-burner liners for AST engines.

4.6 ELECTRONIC CONTROL SYSTEM

A full-authority, digital, electronic control system is critical technology for AST propulsion systems. The ten control system variables listed in Table 4-V for a representative Variable Cycle Engine are a convincing indication that hydromechanical controls would result in an expensive and heavy system which cannot properly fulfill the control function. In contrast with these ten variables, current-technology subsonic commercial engines have only three basic control system variables. For the more complex AST engines, a full-authority digital electronic control system has the potential for numerous improvements relative to an equivalent hydromechanical system. These potential benefits are listed in Table 4-VI.

TABLE 4-V

AST PROPULSION SYSTEM CONTROL REQUIREMENTS
FOR A REPRESENTATIVE VARIABLE CYCLE ENGINE

- Variable geometry inlet
- Variable geometry fan
- Variable geometry compressor
- Primary burner fuel flow
- Augmentor fuel flow
- Variable duct nozzle
- Variable engine nozzle
- Reverser/ejector system
- Flow diverter valve
- Ejector

TABLE 4-VI

POTENTIAL BENEFITS FOR AST ENGINE
ELECTRONIC CONTROL SYSTEM

- Better control accuracy – improved performance.
- Reduced cost and weight.
- Automatic rating schedules.
- Improved maintainability from quick mount computer designs and printed circuit modules.
- Flexibility to reprogram during development.
- Digital data links facilitate integration with inlet control, condition monitoring system, and power management system.
- Self testing capability.
- Self trim capability.

P&WA is presently conducting extensive research and development activity in the area of electronic controls and it is difficult to isolate a portion of this overall effort that has unique meaning to AST engines. Instead, a study program is recommended. This program is subdivided into four tasks:

- Study of closed loop control of convergent-divergent nozzles for optimum performance
- Definition and evaluation of an integrated airplane/engine control system
- Cost effectiveness studies of an AST engine condition monitoring system
- Study of methods for experimentally determining reliability of the electronic control system

4.7 PROPULSION SYSTEM INTEGRATION

The most promising Variable Cycle Engines identified in the Phase II studies will feature most and possibly all of the following unique components:

- Variable geometry supersonic inlets designed for near-sonic internal Mach numbers for noise abatement during take-off and approach
- Low noise coannular nozzles combined with thrust reverser systems
- Low emissions and low noise thrust augmentors
- Variable geometry components including the inlet, fan, compressor, turbine, nozzles, ejector and thrust reverser
- Flow diverter valves
- Structural nacelles for independently supporting the engine, inlet and nozzle/reverser systems
- Advanced airframe and engine accessories
- Acoustic treatment in the exhaust streams
- Digital electronic control and lightweight actuation systems

New design approaches are required to integrate these unique components into an overall propulsion system that provides the reliability, stability, safety and maintenance standards that are critical for the commercial acceptability of an advanced supersonic transport. New concepts for structural support, aerodynamic pod design, thermal management, plus advanced control and actuation systems must be applied to these Variable Cycle Engines. A joint airframe-engine contractor program is recommended to study propulsion system integration. Based on the judgement of both the airframe and engine contractors, a baseline Variable Cycle Engine design will be selected for these integration studies. This integration study will focus on the following areas:

- Overall pod geometry for optimum installed engine performance. Defining the optimum pod dimensions requires intensive trade studies between pod performance and the bare engine performance including weight and cost.

- Inlet characteristics including: inlet/engine structural and aerodynamic interactions; sonic design features for noise abatement; air flow matching characteristics over the entire operating spectrum and corresponding variable geometry requirements for the inlet; and inlet-to-inlet shock interference and unstart interactions.

- Thrust reverser location, targeting and effectiveness requirements and attending effects on the overall pod dimensions.

- Service, inspection and maintenance requirements and nacelle definition that corresponds with these requirements.

- Definition of major engine/airframe interface requirements including engine support locations, thermal management (flow and temperature requirements for the oil and fuel systems), engine airflow bleed requirements, engine power extraction requirements; and airframe accessory definitions.

- Operational procedures for noise abatement and the effect on augmentor and main burner throttling schedules.

- Overall installed engine performance, including nozzle external drag with an ejector, the effects of nacelle secondary cooling requirements, and inlet performance including the effect of boundary layer bleed.

- An integrated airplane/engine electronic control system.

Sensitivity and trade studies conducted throughout this integration study will lead to an optimum pod definition for the selected Variable Cycle Engines. This integration study will provide the background for preliminary design studies of the overall airplane and propulsion systems. It is recommended that this study be conducted in parallel with the engine refinement and conceptual design studies. This parallel effort will enable modification of the refined engine definitions to reflect results of the integration studies.

4.8 REAR VALVE FOR VARIABLE CYCLE ENGINE

The rear flow inverter valve is a new and unique engine component and is therefore a critical technology item for the rear-valve VCE concept. As described in section 3.2.1.2, this valve serves two basic purposes. It inverts the two engine flow streams for the high power mode of operation (the twin turbojet mode). For the alternate mode of operation (part-power subsonic cruise when the duct-burner is off), it mixes the two engine streams together and directs the mixed flow into the rear turbine. This two-position flow switching capability is provided by radial flapper segments controlled by a mechanical actuation system. The rear valve is located in the hot section of the engine and is exposed to 1900°F (1040°C) gas temperatures in both streams during maximum power operation. For other power settings, the temperature difference between the two streams varies to as high as 1500°F (815°C), thus producing high thermal gradients on the valve walls and seals. Furthermore, the valve walls and seals must withstand a total pressure difference of approximately 30 psi (20.7×10^4 N/m^2) at these elevated temperatures. Based on these thermal and structural conditions, as well as the advanced technology design features which have been projected for these valves (low pressure loss, short length and light-weight construction including integral cooling and sealing systems), a technology program is required to quantify and substantiate the design characteristics of these valves.

The overall objective of this program is to establish the weight, aerodynamic and structural characteristics of the flow inverter valve concept and to identify areas of advanced technology that are unique for the valve, especially high-temperature sheet materials, light-weight fabrication techniques, an effective cooling system, high-temperature seals and a fail-safe actuation and control system. This valve program consists of three phases; a series of cold-flow, segmented model tests, a design study, and a large hot-flow, full-annular test. The technology to provide low pressure losses (to eliminate separation at all operating conditions) and reduce the valve length would be evaluated in the first phase consisting of experimental model tests. Ways to incorporate advanced materials, fabrication techniques, seal designs, and effective cooling systems would be conducted in the design phase. These design studies would apply the results of the model test program to minimizing valve length and weight. Transient analysis of the rear-valve VCE concept when making the transition from one mode of operation to the other would also be evaluated in this design phase. The third phase consists of design, fabrication, testing and evaluating a prototype, full-annular valve. This test would closely simulate engine operating conditions including flow rates, temperatures and pressures of the most promising VCE concepts. The valve modes of operation including measurement of flow rates, pressure losses, leakage rates, flow distortion and strut wakes downstream from the valve, separation problems and panel stress and temperature levels. In a separate facility, the valve assembly would be vibration tested to determine the adequacy of the structural design, especially panel flutter at frequencies that might be induced by engine-generated frequencies. Post-test examination of the structural and design and the sealing and cooling systems will identify any problems in the basic valve design. This program would establish the basic feasibility of the valve and would establish a technology base for the overall VCE demonstrator program described in section 4.9.

4.9 APPROACHES FOR AN ENGINE DEMONSTRATION PROGRAM

In addition to identifying critical technology requirements and recommending related programs, various approaches have been formulated for demonstrating these technologies in an AST engine. The basic objective is to integrate the critical AST technologies into a complete engine in order to demonstrate overall benefits, characteristics and interactions of the selected technologies. Three approaches for this demonstrator program have been defined and are depicted in Figure 4.5. This figure also indicates relative costs for these different approaches.

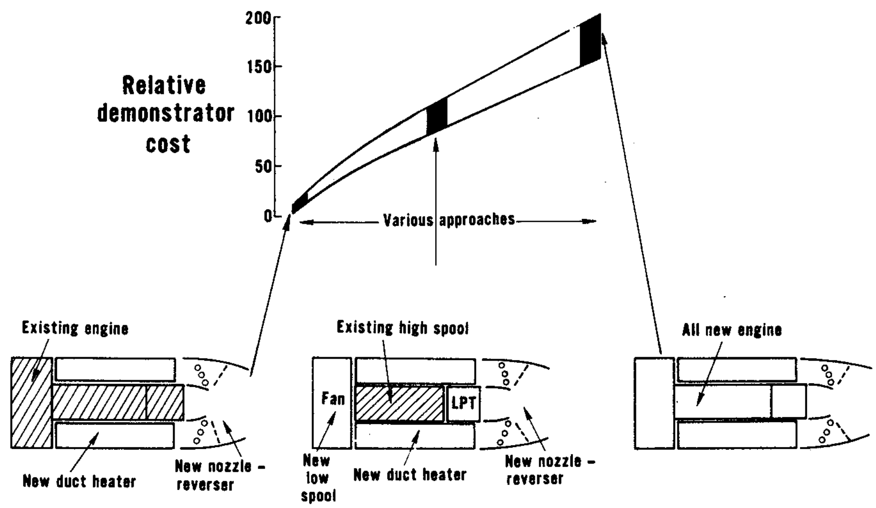


Figure 4-5 *AST VCE Demonstrator Approaches*

The first approach has been defined for minimum cost and entails demonstrating the critical environmental technologies for the two most promising Variable Cycle Engines. These technologies include the low emissions duct-burner and the low noise coannular nozzle. For this approach, experimental configurations of critical components would be applied to an existing engine. Candidate P&WA engines that may be suitable for demonstrating these critical technologies are the F100, the TF30 or the TF33. Each of these turbofan engines can be modified for two separate flow streams, the engine stream and the bypass stream, and can also accommodate an experimental duct-burner and a coannular nozzle system. These modifications can be accomplished without affecting the rotating machinery and support structure of these engines. These AST components would be designed for testing over a range of conditions simulating take-off, supersonic cruise, transonic climb and landing operations. Modifications to the existing engine control systems would be made to provide separate throttle control for the primary burner and the duct-burner. This would allow testing over a broad range of jet exhaust temperatures and velocities to evaluate the coannular noise benefit and corresponding emission levels. This demonstrator approach could include both static and flight testing as well as simulated subsonic and supersonic cruise testing in an altitude chamber. For minimum cost, the experimentatl hardware added to these engines can be designed to withstand flight loads but would not have to be flight-weight in design or construction characteristics. The objectives for this approach are to:

- Evaluate the overall compatibility of a multi-stage fan, a low emissions duct-burner and a coannular nozzle and ejector system designed for low jet noise.
- Determine the coannular nozzle noise benefits with a full-scale engine over a broad set of operating conditions simulating take-off and landing power settings.
- Evaluate the noise characteristics of a duct-burner.
- Evaluate the influence of the duct-burner on aft propagating fan noise.
- Determine the effectiveness of acoustic treatment in the fan duct and along the ejector/nozzle surfaces.
- Measure the sensitivity of ejector configurations on jet noise and possibly on nozzle performance.
- Determine the level of turbine noise and other core noise sources relative to fan and jet noise levels.

These various aspects of the demonstrator program could be evaluated first in a static test program and then either under simulated flight conditions using a moving test vehicle such as a train or a taxiing airplane, or in actual flight by using a flying test bed.

The second demonstrator approach is to use a high spool from an existing engine. The AST technologies that could be demonstrated with this approach include a new low spool (consisting of an AST multi-stage fan, a low pressure turbine, and possibly the unique components for a rear-valve Variable Cycle Engine such as the valve and rear turbine assembly). The duct-burner and coannular nozzle technologies would also be key items in this second approach. In addition to the seven objectives listed under the first approach, this demonstrator would also include:

- Evaluation of the aero/acoustic characteristics of a variable geometry multi-stage fan designed specifically for the requirements of the candidate Variable Cycle Engines.
- Compatibility testing of this multi-stage fan with a supersonic inlet designed for low noise with near-sonic internal Mach numbers during take-off and approach. This would include measuring distortion sensitivity and stability characteristics.
- Evaluation of unique components that constitute a rear-valve Variable Cycle Engine such as the rear-valve and turbine assemblies.

This demonstrator would incorporate all three critical technologies that are unique with AST Variable Cycle Engines; the fan, duct-burner and coannular nozzle. It is therefore a demonstration of the three most critical technologies identified in the Phase II AST studies. If a valved engine concept is chosen for demonstration, the valve, the rear turbine and related unique components and features could be included in this demonstrator engine. Candidate high spools for this approach would be from the following P&WA engines: the F100, the TF30, the TF33 or possibly the ATEGG (Advanced Turbine Engine Gas Generator) high spool.

A third approach is to build an all new demonstrator engine. This would have the capability to demonstrate all of the critical technologies identified in the Phase II studies for the most promising Variable Cycle Engines. It is also the most expensive approach, as shown in Figure 4-5. In addition to the objectives that would be accomplished in the first and second approaches, this new engine approach would include all the advanced technologies associated with the high spools of the candidate Variable Cycle Engines. This includes:

- A new compressor design including advanced aerodynamic and structural features required by the candidate Variable Cycle Engines.
- A low emissions primary burner.
- A high speed, single-stage, high-pressure turbine.
- Advanced cooling and sealing technology systems for the high pressure turbine.
- High temperature materials associated with these high spool components.
- Advanced rotor support concepts that remove bearing compartments from the hot section of the engines.

This all new demonstrator engine could be sized for the actual AST airflow and thrust requirement. It could also be designed with flight-weight components and therefore would be the ultimate demonstrator in terms of the level of AST engine technology that could be tested statically and in flight.

The second and third approaches for this demonstrator program can be extended to include the additional critical technologies that are unique with the rear-valve VCE concept. These additional components are the rear valve, the rear turbine which is part of the low spool, and the nozzle/ejector system. For this rear-valve VCE demonstrator, it may be possible to combine major components from existing engines, especially the fan and the complete high spool (compressor, main burner and high pressure turbine) to minimize program costs and to concentrate on the unique critical technology components.

Table 4-VII summarizes the critical technology areas and operating conditions that can be demonstrated with each of these three approaches.

TABLE 4-VII

CRITICAL TECHNOLOGIES AND OPERATING CONDITIONS TO BE DEMONSTRATED WITH EACH APPROACH

Critical Technologies for Variable Cycle Engines	Demonstrator Engine Approach 1	2	3
Coannular Nozzle	Yes	Yes	Yes
Duct-Burner	Yes	Yes	Yes
Multi-Stage Variable Geometry Fan	Partially	Yes	Yes
High Spool Technology	No	No	Yes
Electronic Control System	Optional	Optional	Optional
Rear-Valve VCE Components	No	Yes	Yes
Operating Conditions			
Simulated Take-off and Landing Conditions for Measuring Noise and Emission Characteristics	Yes	Yes	Yes
Simulated Supersonic Operation for Measuring Performance and Emissions	Yes	Yes	Yes*
Flight Test Capability			
Subsonic	Yes	Yes	Yes
Supersonic	No	Yes	Yes

*May be limited by altitude simulation facilities because of large engine size.

Figure 4-6 indicates the relationship between the critical technology programs recommendations and these demonstrator engine programs. The basic research programs for each critical technology would be conducted first. These programs would provide the foundation for preliminary design of the major components for the most promising Variable Cycle Engines including design studies for each of the demonstrator engine approaches. As indicated by the star-enclosed items, results from the on-going AST/SCAR studies and other related programs such as the NASA-sponsored Experimental Clean Combustor Program for primary burners would also be factored into these preliminary design studies. At this point, the engine demonstration program can be initiated, starting with the minimum cost approach (No. 1 in Table 4-VI). Using a building-block technique, additional critical technology items listed in Table 4-VII for approaches 2 and 3 can be picked up as this demonstration program progresses.

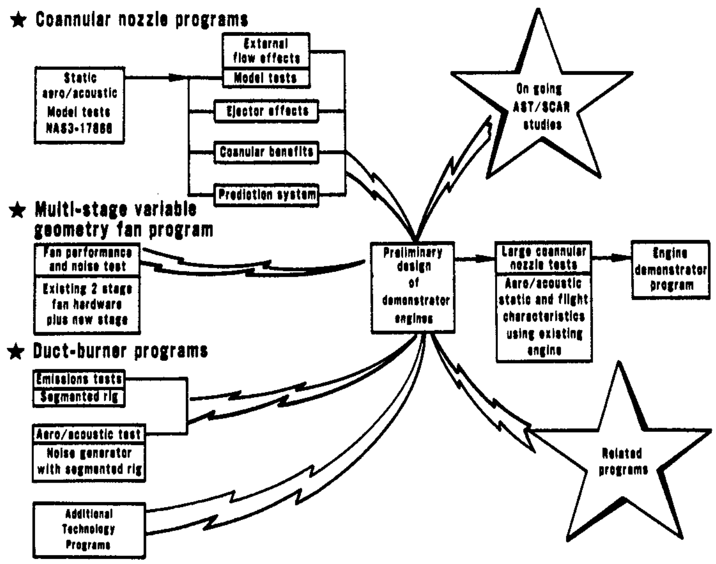


Figure 4-6 *Critical Technology Programs for Variable Cycle Engines*

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LIST OF ABBREVIATIONS

AIV	Annulus Inverting Valve
AST	Advanced Supersonic Technology
BPR	bypass ratio
°C	degrees Celsius
CET	combustor exit temperature
Cv	nozzle velocity coefficient
CO	carbon monoxide
DHTF	Duct-Heating Turbofan
DOC	direct operating cost
DOT	Department of Transportation
ECCP	Experimental Clean Combustor Program
EGV	exit guide vane
EPA	Environmental Protection Agency
EPNdB	effective perceived noise decibels
°F	degrees Fahrenheit
FAR-36	Federal Aviation Regulation - Part 36
Fg	gross thrust
Fn	net thrust
FPR	fan pressure ratio
IGV	inlet guide vane
ft	feet
ITS	Inverse Throttle Schedule
°K	degrees Kelvin
kg	kilograms
km	kilometers
lb	pounds
LBE	Low Bypass Engine
LCF	low cycle fatigue
L/D	lift/drag ratio
L/H	length/height ratio (of an annular passage)
LPT	low-pressure turbine
m	meters
MCE	Multi-Cycle Engine
Mn or M	Mach number
N	Newtons
nm or N.MI.	nautical mile
NO_X	oxides of nitrogen
N/R/S	nozzle/reverser/suppressor system
OEW	operating weight empty
OPR	overall pressure ratio
pps	pounds per second
psi	pounds per square inch
PTO	power takeoff
R.F.	range factor ~V (L/D)/TSFC
ROI	return on investment
SCAR	Supersonic Cruise Airplane Research
sec	second
SLS	sea level static.

LIST OF ABBREVIATIONS (Cont'd)

SO_2	sulfur dioxide
STD	standard day
SST	Supersonic Transport
THC	total hydrocarbons (unburned hydrocarbons)
TOGW	take-off gross weight
TSFC	thrust specific fuel consumption
VCE	Variable Cycle Engine
VGT	variable geometry turbine
VSCE	Variable Stream Control Engine
WAT	total airflow
ZFW	zero fuel weight

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